The influence of losses in the core of an inductor on characteristics of the boost converter

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Abstract. In the paper the influence of core losses on characteristics of the boost converter is considered. In calculations, the average electrothermal models of the diode-transistor switch and of the inductor are used. The applied electrothermal models and the obtained results of calculations are presented. The selected results of calculations are compared with the results of measurements. The influence of such factors as converter load resistance and frequency of the control signal and lossiness of the core on characteristics of the considered converter and the loss of energy in the inductor are discussed.

1. Introduction
Boost converters are widely used sub-circuits of switched-mode power supplies, and they are characterized by high watt-hour efficiency [1, 2, 3]. To miniaturize dimensions of these devices an increase in switching frequency of electronic components is required.

The inductor included in boost converters is the basic element for energy storage and its properties influence characteristics of the considered circuit [4, 5, 6]. During the inductor operation, self-heating phenomena and mutual thermal interaction between the core and the winding of the inductor are observed [7, 8, 9]. The source of heat generated in the inductor are losses in the core and in the winding. As presented in paper [7, 8, 10] the inductor core characteristics strongly depend on magnetic material used to build this core and it well describes its dependence of the magnetic flux density B on the magnetic force H, which takes the shape of a hysteresis loop.

For the analysis and design of electronic circuits computer programs such as SPICE are used [11, 12, 13]. In many papers concerning the analysis of dc-dc converters only energy losses in semiconductor devices are taken into account [11, 12, 14 - 17], whereas losses in magnetic elements are omitted. In paper [5] the electrothermal model of an inductor dedicated for SPICE, which takes into account power losses in the core and a self-heating phenomenon is proposed. This model is dedicated to simulate dc-dc converters using the transient analysis, which is time-consuming [14]. Reduction in the duration time of calculations is ensured for the use of an average model of the inductor proposed in papers [18, 19]. These models allows calculating the non-isothermal characteristics of non-isolated dc-dc converters using the DC sweep analysis in SPICE.

In this paper, the influence of power losses of the inductor core on characteristics of the boost converter is analyzed. The calculations are made using the average electrothermal model of the diode-
transistor switch, presented in paper [15], and the average electrothermal model of the inductor, presented in paper [18], for converters containing cores made of different magnetic materials. The calculations are performed for different frequency of operation and converter’s load resistance. The selected results of calculations are compared with the results of measurements.

In the second section the average models of components of the considered converters are shortly described, whereas in the third section the results of calculations and measurements are presented.

2. The used models
The analysis is performed using average electrothermal models of the diode-transistor switch and of the inductor, elaborated previously by the authors. In paper [19], usefulness of such a model for the analysis of boost converters at the steady state is proved. The network representation of these models are presented in Figs. 1 and 2, respectively.

![Figure 1. Network representation of the average electrothermal diode-transistor switch model [15].](image)

The average electrothermal model of the diode-transistor switch takes into account energy losses for the switch-on semiconductor devices and a self-heating phenomenon. Additionally, this model allows determining characteristics of dc-dc converters operating in the CCM and DCM modes.

In Figure 1, the series connected control voltage sources Et and Er represent the unipolar transistor, whose output terminals are connected to terminals 1 and 2 and the control terminal is connected to the terminal 5, while the diode (between the terminals 3 and 4) is represented by the controlled current source Gd. The independent voltage source V1 of zero output voltage is used to control the diode average current, elements Ga, Ra, Va, Eu are the auxiliary circuit, which is used to determine the mode of dc – dc converter (CCM or DCM) including the considered switch. The controlled voltage sources Eron, Erd, Eud model temperature changes of transistor resistance R_{ON}, series diode resistance R_D and voltage U_D on the forward biased p-n junction. The value of the internal diode and transistor temperature are calculated using the voltage sources Etd and Ett. The detailed description of the controlled voltage sources efficiency contained in the considered model is presented in [15].

In turn, in the average electrothermal model of the inductor there are three blocks: the main circuit, auxiliary circuits and the thermal model. Terminals A and B are the terminals of the inductor. Additionally, the terminal L provides the voltage corresponding to the inductor inductance, terminal T_U - the temperature of the inductor winding and terminal T_R - the temperature of the inductor core.

In the main circuit the voltage source V_L with zero output voltage monitors the current of the inductor, the resistor R_{SO} represents the winding resistance of the inductor for the direct current at the reference temperature T_0 and the controlled voltage source E_{RS} describes the influence of temperature and losses of the inductor series resistance. In turn, the controlled voltage source E_{RN} models the skin effect phenomenon.

In the auxiliary block the controlled voltage sources are used to calculate the value of the magnetic
force $H$, flux density $B$, saturation flux density $B_{\text{sat}}$ and the auxiliary value $C$. The description of efficiency of these sources is given in [9]. The controlled voltage sources $E_{\text{LS}}$ model the dependences of the inductor inductance $L$ of the current, frequency and temperature.

The thermal model allows calculating an excess of the core temperature $T_R$ and winding $T_U$ above the ambient temperature $T_a$. To determine these excesses the compact thermal model is used, in which the controlled voltage sources $E_{\text{TR}}$ and $E_{\text{TU}}$ are used to calculate the value of these temperatures taking into account a self-heating phenomenon in the core and winding and mutual thermal interactions between the core and the winding.

The total power losses occurring in the ferromagnetic core (representing by the voltage source $E_{\text{PR}}$) are the sum of losses connected with hysteresis losses, eddy current losses and remaining losses. The kind of losses which are dominant is determined by the type of magnetic material, the peak value of flux density, frequency and the shape of flux density [5]. Losses in the core are also characterized by power losses of the core per unit of volume or mass [7]. For a sine wave of induction, core losses are described by the formula given in [18]. In dc-dc converters the inductor current has the shape of a triangle wave. In this case, core losses can be described by the formula

$$P_R = V_e \cdot P_{V_0} \cdot f R^\alpha \cdot 2^\alpha \cdot \left(1 + \alpha_p \cdot (T_R - T_m)^{\beta P}\right) \left(d^{1-\alpha} + (1-d)^{1-\alpha}\right)$$

(1)

where $V_e$ denotes the equivalent volume of the core, $P_{V_0}$ - volumetric power losses density in the core, $\alpha, \beta$ are parameters depending on magnetic material, $B_m$ – the amplitude of flux density, $\alpha_P$ represents the temperature coefficient of power dissipated in the core, $T_m$ is the value of the core temperature, at which power losses in the core have the minimum, $f$ denotes frequency and $d$ is the control signal duty cycle of the converter.

On the other hand, powers dissipated in the core and winding $P_U$ is determined by means of the controlled voltage source $E_{\text{PLU}}$. This power is described by the formula

$$P_U = u_{\text{RS}} \cdot i + u_{\text{RN}} \frac{\Delta_l}{2}$$

(2)

The voltage $U_{\text{RS}}$ and $U_{\text{RN}}$ occurring in the formula (2) are shown in Figure 2. The peak to peak value of the current $\Delta l_c$ and flux density amplitude $B_m$ correspond to the voltage value on the controlled voltage sources EDIL and EDB, respectively. The values of these quantities are described by the formulas

$$\Delta l_c = \frac{u_{\text{RS}} - u_{\text{RN}} - V_{\text{sat}}}{L \cdot f} \cdot d$$

(3)
\[ B_m = \frac{L \cdot \mu_0 \cdot I_{Fe} \cdot z \cdot \Delta I_i}{2 \cdot (I_{Fe} + I_p)} \left( \mu_0 \cdot z^2 \cdot S_{Fe} - L \cdot I_p \right) \]  

(4)

where \( u_{we} \) denotes the converter input voltage, \( V_{on} \) – the voltage on the active transistor contained in the converter (voltage at the source Et of Figure 1), \( z \) denotes the number of turns in the inductor winding, \( S_{Fe} \) – effective cross-section area of the core, \( I_{Fe} \) – the magnetic path in the core, \( I_p \) – the air gap length, \( \mu_0 \) – magnetic permeability of free air.

3. The results of calculations and measurements

In order to investigate the influence of losses in the core of the inductor on characteristics of the boost converter some measurements and calculations of the considered converter, whose diagram is presented in Figure 3, are performed. In the considered network the transistor MOSFET of the type IRF540, the Schottky diode 1N5822 and passive elements of the following values: \( R_G = 30 \Omega \), \( C_1 = 47 \mu F \) are applied. The resistor \( R_0 \) represents load resistance of the converter, and the voltage source \( U_{we} \) - the power supply of the output value equal to 12 V.

![Figure 3. Diagram of the considered boost converter.](image)

In the considered converter, the investigations are performed for inductors with ring cores of the diameter equal 26 mm made of ferrite (the core RTF), of powdered iron (the core RTP) and of nanoperm (the core RTN). On each core 27 turns of the copper wire in the enamel of the diameter 0.8 mm are wound. In Figure 4 the calculated dependences \( L(i) \) of the considered inductors are shown.

![Figure 4. Calculated dependences L(i) for the investigated inductors.](image)

As it is visible, depending on material of the applied core very different courses of the dependence \( L(i) \) for the considered inductors are obtained. Inductance of the inductor with the core RTP is practically constant in the considered range of changes of the current and is about 80 \( \mu H \). In turn, inductance of inductors with the cores RTF and RTN strongly depends on the current. For example, for the inductor with the core RTN, in the considered range of changes of the current, a fall in the value of inductance from above 50 mH for \( i = 10 \) mA to 95 \( \mu H \) for \( i > 1 \) A is visible.

The considered inductors differ between each other not only is the course of the dependence \( L(i) \), but also in the values of parameters occurring in equation (1) and describing a power loss in the core. The values of these parameters are collected in Table 1.
Table 1. Values of parameters characterizing power losses in the cores of the considered inductors.

| Core | $P_{V_0}$ [Ws°/(m°T²)] | $\alpha$ | $\beta$ | $\alpha_\varphi$ [K²] | $T_m$ [K] | $V_e$ [m°] |
|------|--------------------------|---------|--------|---------------------|----------|---------|
| RTF  | 2.76                     | 1.24    | 2.28   | 2x10⁴               | 343      | 3.14x10⁶|
| RTN  | 0.05                     | 1.69    | 2.2    | 0                   | 358      | 3.95x10⁶|
| RTP  | 103                      | 1.15    | 2.07   | 0                   | 361      | 4.43x10⁶|

In Table 1 the considerable differentiation of the value of lossiness $P_{V_0}$ for the considered cores is visible. It accepts values from the section from 0.05 to 103 Ws°/(m°T²). It should be expected that this differentiation will influence also courses of characteristics of converters containing the considered inductors.

In Figure 5 the calculated (lines) and measured (points) characteristics of the boost converter containing in turn each of the investigated inductors are presented. The calculations and measurements are performed at frequency of the control signal $f = 50$ kHz and the duty cycle $d = 0.5$.

![Figure 5](image)

**Figure 5.** Calculated and measured dependences of the output voltage (a), watt-hour efficiency (b) of the boost converter and core temperature of the inductor (c) on load resistance.

As one can notice, the dependence $U_{wy}(R_0)$ within the range of small values of load resistance (when the converter operates in CCM) has practically the identical course for all the inductors. In turn, material of the core decides about the value of resistance $R_0$ at which the converter passes from the mode CCM to DCM. For the converter with the inductor containing the core RTP this passage appears at resistance $R_0$ equal to about 100 Ω, and for the converter with the inductor containing the core RTN - at resistance $R_0$ equal to about 3 kΩ. Unfortunately, the obtained by means of the presented models calculated values of watt-hour efficiency are overestimated with regard to the measured values of this parameter, and the calculated values of temperature of the core are typically understated.

The dependences of the converter output voltage, watt-hour efficiency and core temperature on load resistance of the considered converter including the inductor with the RTF core at different values
of the parameter $P_V$ equal to values 0.01, 2.7, 80 and 150 Ws$^a$/m$^3$T$^b$, respectively are presented in Figure 6. Research is conducted in the function of load resistance, at the constant value of frequency $f = 50$ kHz and the duty cycle of the control signal $d = 0.5$.

As it is visible for load resistance $R_0$ in the range from 10 $\Omega$ to about 1 k$\Omega$ (when the converter operates in the CCM mode) an increase in $P_V$ loss causes a decrease in the output voltage up to 40% and a decrease in watt-hour efficiency - about 30% for load resistance higher than 10 $\Omega$, and up to a three-fold increase of the core temperature $T_R$ for load resistance $R_0 < 100$ $\Omega$. Power dissipated in the core does not exceed 1.5 W, and its value is the biggest in the range of small load resistance. As expected, an increase in the value of the parameter $P_V$ causes an increase in the value of power dissipated in the core of the inductor.

![Figure 6](image-url)

**Figure 6.** Dependence of the converter output voltage (a), watt-hour efficiency (b) and inductor core temperature of the considered boost converter (c) and power dissipated in the core (d) on load resistance for different values of parameter $P_V$.

The dependences of the converter output voltage, watt-hour efficiency and core temperature as a function of load resistance of the considered converter with the ferrite core at different frequency equal to 50, 100 and 400 kHz, respectively are presented in Figure 7. As one can notice, with an increase of frequency of the control signal the point of passages of the considered converter into DCM moves to higher values of load resistance. It is proper to draw attention to the fact that only at frequency of the control signal $f = 400$ kHz the boost converter in the whole considered range of load resistance operates in CCM. One observes also not a large influence of frequency of the control signal on watt-hour efficiency. Whereas, temperature of the core is a decreasing function of load resistance and it is weakly depends on frequency.
4. Conclusions
The paper presents the influence of power losses in the core inductor on characteristics of the boost converter. This effect is studied on the basis of the proposed earlier averaged electrothermal models of a diode-transistor switch and the modified average electrothermal model of an inductor. The results show that the inductor core losses significantly affect characteristics of the considered boost converter operating in the CCM mode. An increase of loss causes a significant reduction of the output voltage and shifts the boundary between the CCM and DCM modes towards smaller values of load resistance. On the other hand, in the range of large and very small currents, the influence of losses on the output voltage of the boost converter is not observed, which means that in this range losses in the winding are dominant.

Investigations performed for the converter containing cores made of different materials show that the material of the core caused essential changes of inductance of the inductor and in a decisive manner influenced the value of load resistance at which the border between the modes CCM and DCM appear.

Additionally, one observes the essential influence of frequency of the control signal on the dependence $U_{wy}(R_0)$ over load resistance $R_0 = 1 \, k\Omega$. With an increase of frequency follows the shift of the point of passage of the converter in the DCM mode of operation. Whereas, one does not observe influence of frequency on watt-hour efficiency of the considered converter.

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