The results of the study on the effect of the design parameters of a nonlinear inductor on the level of electromagnetic interference generated by DC/DC converters are presented. The paper proposes models designed for the LTspice XVII environment, which allow investigating conducted interference spectra, efficiency and output voltage ripple of the converter using a nonlinear inductor model. The simulation results showed that the level of conducted interference is affected by the volume and material of the inductor core, as well as the presence of an air gap in the core. The results of measurements of conducted interference spectra at different values of the cross-sectional area of the inductor core of the DC/DC converter are presented. With the nominal cross-sectional area of the core, calculated taking into account converter output power, the study of the relationship between the level of conducted interference and the width of air gap in the inductor core is carried out. In the course of studies, using the Chan model, the influence of inductor core material on the level of interference generated by the DC/DC converter is analyzed. Analysis of the influence of the width of the air gap in the inductor core on the level of conducted interference is carried out. It is shown that air gap width should be selected taking into account inductor core material. Simulation results for a number of commonly used materials made it possible to determine the most effective one in terms of generated interference.

The results obtained in the analysis of switching voltage converter operation, taking into account inductor nonlinearity, allow us to formulate recommendations to reduce the level of generated conducted interference by 4.5 to 6 dB due to the correct choice of inductor material and design parameters

Keywords: conducted interference, interference spectrum, nonlinear inductance, core material, air gap

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ANALYSIS OF THE INFLUENCE OF INDUCTOR SATURATION ON THE LEVEL OF ELECTROMAGNETIC INTERFERENCE OF DC/DC-CONVERTERS

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1. Introduction

Today, under an intense expansion of the functional capabilities of radio-electronic equipment, accompanied by an increase in its sensitivity, there is an obvious need to increase attention to electromagnetic compatibility of the developed device with other devices and the electric network.

Since any radio-electronic equipment requires power, it should be borne in mind that power supplies can generate interference. As the overwhelming number of power supplies operate in the switching mode, the level of interference created by such sources in current pulse switching is very significant. Therefore, when designing switching converters, attention is needed not only to efficiency, weight and dimensions, but also to the levels of interference created by such converters.

When designing a highly efficient DC/DC converter, the problem always arises to find a compromise between high efficiency, weight and dimensions, and cost. The dimensions of the DC/DC converter largely depend on the dimensions of the transformer or inductor, and their dimensions, in turn, on the amount of energy used during converter duty cycle. However, many such converters are also subject to electromagnetic compatibility requirements.

When simulating the operation of such devices, linear models of inductors and transformers are used to analyze the level of electromagnetic interference (EMI), which do not take into account core saturation and nonlinearity of magnetization characteristics. Therefore, the simulation results and the level of interference generated by converters may not be the same in practice. To a large extent, this difference can be noticeable at maximum load currents.

Taking into account the influence of nonlinearity of magnetization characteristics of inductors in the design of switched-mode power supplies will allow formulating recommendations to minimize the effect of this phenomenon on the level of electromagnetic interference.

Reducing the level of converter interference will either eliminate the need for interference filters, or significantly reduce the requirements for them. This, in turn, will reduce the size and cost of converters.

2. Literature review and problem statement

The work [1] presents the results of studies on the effect of the cross-sectional area of the inductor core on the interference level of the DC/DC converter. But questions remained about the effect of the nonlinearity of the magnetization characteristic of the core, core material and air gap in the core on the level of electromagnetic interference created by the converters.

Various models of nonlinear inductance are given in [2–5].

In [2], a model of nonlinear inductance is proposed and an example of modeling a switched-mode power supply using the proposed model is given. However, the work does not consider measuring and minimizing the level of electromagnetic interference.

In [3], the issues of designing transformers, taking into account the nonlinearity of the magnetization characteristic, intended for switched-mode power supplies are examined. The main attention is paid to the determination of losses in transformers for different design parameters. However, the relationship between the transformer core parameters and the level of converter interference is not considered.

In [4], a mathematical model of inductance with a ferromagnetic core is considered and the operation of such inductance, when connected to an alternating current circuit with a frequency of 50 Hz, is simulated. The main task of the study was not only to create a model, but also to experimentally verify that it complies with real inductor parameters. However, the use of such a model in switched-mode power supplies is not examined.

Almost all cases of designing switching voltage converters do not take into account the nonlinear relationship between the inductor (or transformer) inductance and the current flowing through it. In [5], the effect of inductance nonlinearity on power losses is studied. However, the analysis of the influence of inductor nonlinearity on the level of EMI created by switching voltage converters is not carried out.

In [6], transformer operation is investigated taking into account the nonlinearity of the inductor made of electrical steel. The objective of the study was to determine losses in the magnetic core during transformer operation at a frequency of 50 Hz. The calculation of inductor design parameters for operation at high frequencies is not addressed.

In [7], a method for calculating and selecting an inductor for switching voltage converters is given. It takes into account only the input and output converter voltage, maximum inductor current and power switch frequency. The issue of calculating the design parameters – magnetic core volume, cross-sectional area of the core, air gap in the core is not considered.

In [8], it is proposed to calculate inductance, taking into account input and output voltage, minimum and maximum load current and converter switch frequency. In addition, graphs of inductance depending on the DC component of current and on operating temperature are shown. However, there is no calculation of inductor design parameters.

Analysis of the effect of inductor parameters on the EMI level is not performed in [6–8].

In [9], the choice of materials and calculation of geometric parameters of the core are substantiated in detail, the value of magnetic flux through the inductor for the given converter parameters is determined, but no analysis of the EMI level of such a converter is carried out.

Based on the analysis, it can be concluded that the influence of the magnetic core of transformers and inductors on EMI levels is practically not studied in the literature. All inductive components used are generally assumed to operate in a linear mode. When simulating the operation of such devices and analyzing the EMI level, linear models of inductors and transformers are used that do not take into account the nonlinearity of their magnetization characteristics. This leads to discrepancies between simulation and practical results. To a large extent, these differences can be noticeable at maximum converter load currents. An attempt to analyze the effect of the nonlinearity of the magnetic characteristics of the core on the level of EMI generated by switching voltage converters is made in [1].

It follows from [1] that when choosing a core for transformers or inductors of a switching voltage converter, it is not enough to take into account the required converter power. It is also necessary to take into account the level of electromagnetic interference generated by the converter, which complicates the calculation of core parameters.

Compliance of switching converters with electromagnetic compatibility standards can be ensured by the complex application of various interference reduction methods and interference suppression means.

Determining the effect of different design parameters of magnetic inductor cores on the level of electromagnetic interference will allow formulating recommendations to take these factors into account when designing switched-mode power supplies. On this basis, it is advisable to conduct a study on the effect of inductor nonlinearity on the level of interference created by switching voltage converters.

3. The aim and objectives of the study

The aim of the study is to find ways to reduce the level of conducted interference generated by switched-mode power supplies.

To achieve the aim, the following objectives are set:

– to develop a converter model that allows taking into account both inductor design parameters and core material characteristics;

– to analyze the influence of inductor core saturation on the level of interference generated by converters when changing the core cross-sectional area and air gap width;

– to analyze the influence of the core material on the interference level and formulate recommendations for inductor material and design parameters, which will reduce interference.

4. Results of studying the effect of inductor design parameters on the level of conducted interference

4. 1. Development of a model to analyze the effect of inductor nonlinearity

Any DC/DC converter contains inductors or transformers (except for converters on switched capacitors), capacitors and transistor switches. Inductance depends on the maximum initial current, input and output voltage, power switch frequency and level of output voltage ripple.

The LTspice program, developed by LinearTechnology (USA), uses a modified nonlinear model of the inductor (transformer) core with hysteresis. The literature [2, 4, 5] provides several different models of nonlinear inductance. To analyze the effect of the nonlinearity of inductor characteristics, we use the model given in [2].

This model defines a hysteresis loop with only three parameters:

– H_c – coercive force (A/m);

– B_r – remanent induction (T);

– B_s – saturation induction (T).

The ascending and descending sections of the hysteresis curve are described by the following expressions:

$$B_{up}(H)=B_s(H+H_c)/\left[\begin{matrix}|H+H_c|+\\+H_c(B_s/B_r-1)\end{matrix}\right]+m_0H, \quad (1)$$

and

$$B_{dn}(H)=B_s(H-H_c)/\left[\begin{matrix}|H-H_c|+\\+H_c(B_s/B_r-1)\end{matrix}\right]+m_0H. \quad (2)$$

The magnetization curve is described by:

$B_{mag}(H)=0.5[B_{up}(H)+B_{dn}(H)]$.

Along with hysteresis loop parameters, when describing nonlinear inductance, design parameters of nonlinear inductance are taken into account – linear dimensions of the core and number of turns.

Design parameters of the inductor magnetic core:

– L_m – length of the middle magnetic line of the core (m);
– L_g – width of the air gap (m);
– A – cross-sectional area of the core (m^2);
– N – number of turns.

Consider an example of determining the design parameters of the inductor core of the boost converter with the following parameters:

– input voltage V_{in}=12V;
– output voltage V_{out}=24 V;
– output current I_{out}=2 A;
– power switch frequency F_{SW}=100 kHz.

To determine core design parameters, it is necessary to determine the parameters that describe the magnetic properties of the material. Let us make the calculation by the methodology given in [10]. The calculation methods given in [7–9] do not take into account the nonlinear dependence of inductor parameters on load current.

Let us determine the output and converted power P_{CP} for the boost converter [10]. The weight, dimensions and cost are mainly influenced not by the output, but by the converted power P_{CP} – part of the energy transmitted through the magnetic or electric fields of the elements. In this example, this process occurs in inductor L1. Therefore, all other circuit parameters depend on its operating mode.

In general, the amount of converted power can be less than the converter power. This is due to the fact that some of the energy is supplied to the load directly from the input voltage source. Maximum energy consumed during the duty cycle, output and converted power are calculated by the formulas:

$$P_{out}=V_{out}\cdot I_{out}=24\cdot 2=48\text{ W}, \quad (3)$$

$$P_{CP}=P_{out}\left(1-\frac{V_{in}}{V_{out}}\right)=24\text{ W}, \quad (4)$$

$$W_{\max}=\frac{P_{CP}}{F_{SW}}=\frac{24}{100\cdot 10^3}=0.24\cdot 10^{-3}\text{ J}. \quad (5)$$

where $W_{\max}$ is the maximum energy consumed during the duty cycle of the converter.

Electrical parameters with magnetic ones are related by the following expression:

$$W_{\max}=\frac{B_M\cdot B_{AVG}}{\mu_0\cdot\mu_{eq}}AL_m, \quad (6)$$

where μ_0 is the magnetic permeability of vacuum (1.257×$\times 10^{-6}$ H/m), μ_{eq} is the equivalent magnetic core permeability taking into account the design features, B_M is the ripple range of magnetic induction, B_{AVG} is the average value of magnetic induction.

The volume of the magnetic core AL_m can be calculated by the formula:

$$AL_m\geq W_{\max}\frac{\mu_0\cdot\mu_{eq}}{B_M\cdot B_{AVG}}. \quad (7)$$

The choice of the core material is determined by factors such as power loss at the converter frequency and its cost. Choosing the most expensive option, we can get an almost 4 times gain relative to the power loss in the core with the cheapest option. We choose molypermalloy powder as the material with the following parameters: μ_{eq}=60, B_r=0.35 T, B_s=0.75 T [11, 12]. Let us find the missing parameters:

$$B_{\max}=0.75B_s=0.75\cdot 0.7=0.525\text{ T}, \quad (8)$$

$$B_{m\_\max}=B_{\max}-B_r=0.525-0.35=0.175\text{ T}, \quad (9)$$

$$B_M=0.3B_{m\_\max}=0.0525\text{ T}, \quad (10)$$

$$B_{AWG}=B_{\max}-0.5B_M==0.525-0.5\cdot 0.0525=0.4988\text{ T}. \quad (11)$$

The range of allowable magnetic core volume for molypermalloy powder based on standard sizes is 0.06...45.34 cm^3. Determine the minimum allowable magnetic core volume $V_{\mathbf{min}}$ to select the core model:

$$V_{\min}\geq W_{\max}\frac{\mu_0\cdot\mu_{eq}}{B_M\cdot B_{AVG}}==0.24\cdot 10^{-3}\left(\frac{1.257\cdot 10^{-6}\cdot 60}{0.0525\cdot 0{,}4988}\right)=0.69\text{ cm}^3. \quad (12)$$

For molypermalloy powder when the converter operates in a continuous mode, a typical DM166-60 (55121) core with a cross-sectional area A=0.2 cm^2, magnetic core volume $V_{\min}$=0.86 cm^3, magnetic line length L_m=4.21 cm is suitable.

Determine the number of coil turns N:

$$N=\frac{U_{out}\cdot t_{dc}}{AB_M}=\frac{24\cdot 8\cdot 10^{-6}}{0.0525\cdot 20\cdot 10^{-6}}=152.3\approx 153, \quad (13)$$

where t_{dc} is the converter duty cycle.

To find the coercive force, consider that this parameter is associated with the power losses specified for each material in the reference book.

For molypermalloy powder at a frequency of 100 kHz and magnetic flux of 0.5 T, the specific loss power will be P_{loss}=102 mW/cm^3. Thus, the total loss power P_{floss} will be:

$$P_{floss}=P_{loss}\cdot V_{\min}=0.12\cdot 0.86=0.103\text{ W}. \quad (14)$$

To find the coercive force, we introduce all the parameters found into the Chan model, setting the generator frequency to 100 kHz and magnetic flux b=0.5 T (Fig. 1). The value of the coercive force must satisfy the loss power parameter according to the reference data for molypermalloy powder.

Simulation settings

```
.tran 0 {1.25/f} {0.25/f} {0.5/f} uic
.param b=0.5 f=100 Lm=4.21 A=0.00002 N=153
Hc = 9 Br = 0.35 Bs = 0.75 Lm = {Lm} Lg = 0 A = {A} N = {N}
```

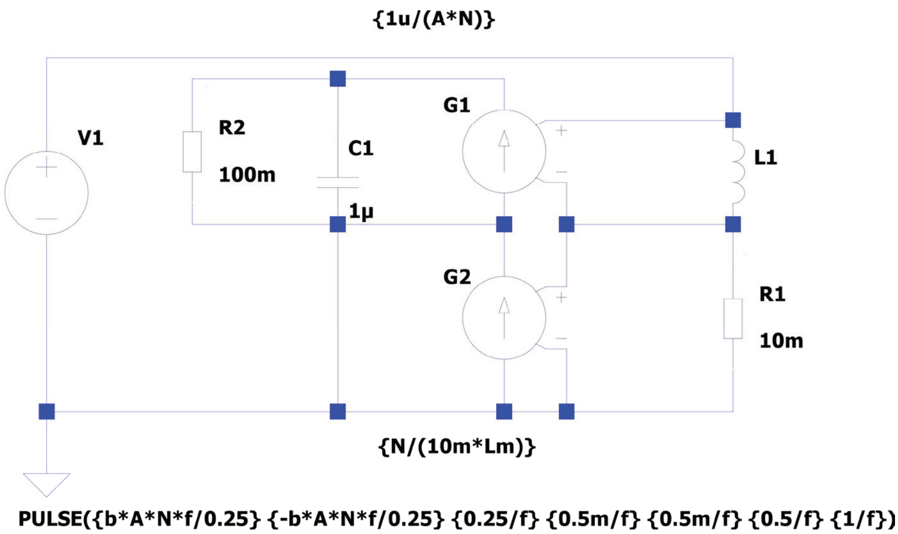
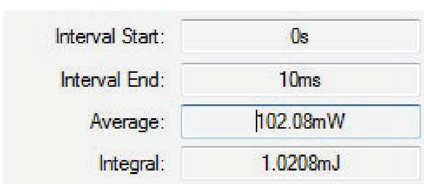


Fig. 1. Modeling nonlinear inductance using Chan model

With a coercive force H_c=9 A/m, we obtain the power of inductor losses, which coincides with the reference value for molypermalloy powder (Fig. 2).



Interval Start:	0s
Interval End:	10ms
Average:	102.08mW
Integral:	1.0208mJ

Fig. 2. Average loss power at nonlinear inductance

The hysteresis loop cycle for the molypermalloy powder core is shown in Fig. 3.

Using the obtained values that characterize the magnetic material for the Chan model, we determine the current at which the inductor will enter the saturation mode [2]. The inductor current at any time can be calculated by the formula:

$$I(t)=\frac{H(t)\cdot L_m}{N}. \quad (15)$$

With a narrow hysteresis loop, the law of variation of magnetic field strength $H(t)$ repeats that of induction $B(t)$ in the time domain:

$$H(t)=\frac{B(t)}{\mu\cdot\mu_0}. \quad (16)$$

Taking into account (15) and (16) for molypermalloy powder, the saturation current I_{sat} is calculated by the formula:

$$I_{sat}=\frac{B_s\cdot L_m}{N\cdot\mu\cdot\mu_0}=$$
$$=\frac{4.21\cdot 0.75}{153\cdot 1.257\cdot 10^{-6}\cdot 3{,}600}=$$
$$=4.5\text{ A}. \quad (17)$$

To analyze the switching converter operation, we use the model shown in Fig. 4. The converter is based on the LT3757 controller, which allows varying both the input and output converter voltage within significant limits.

Let's simulate the operation of the boost converter using a hysteresis inductor with the parameters calculated above. The input and output parameters of the converter coincide with those specified for the design parameters of the inductor: V_{in}=12V, V_{out}=24 V, I_{out}=2 A, F_{SW}=100 kHz.

The LT3757 controller operates over a frequency range of 100 kHz to 1 MHz, which is set by the resistor R1. At R_1=140 kOhm, the converter operating frequency is F_{SW}=100 kHz.

In the model shown in Fig. 4, the start and duration of the simulation process, as well as the start time of saving the simulation results, is set by the .tran directive. The .four directive allows Fourier analysis of the converter input current I (V1). The .meas directive determines converter efficiency by processing the data obtained from the simulation of initial data. The result is assigned to the eff variable, which corresponds to the ratio of the RMS power consumed by the load to the power consumed from the input voltage source – $eff=P_{out}/P_{in}$.

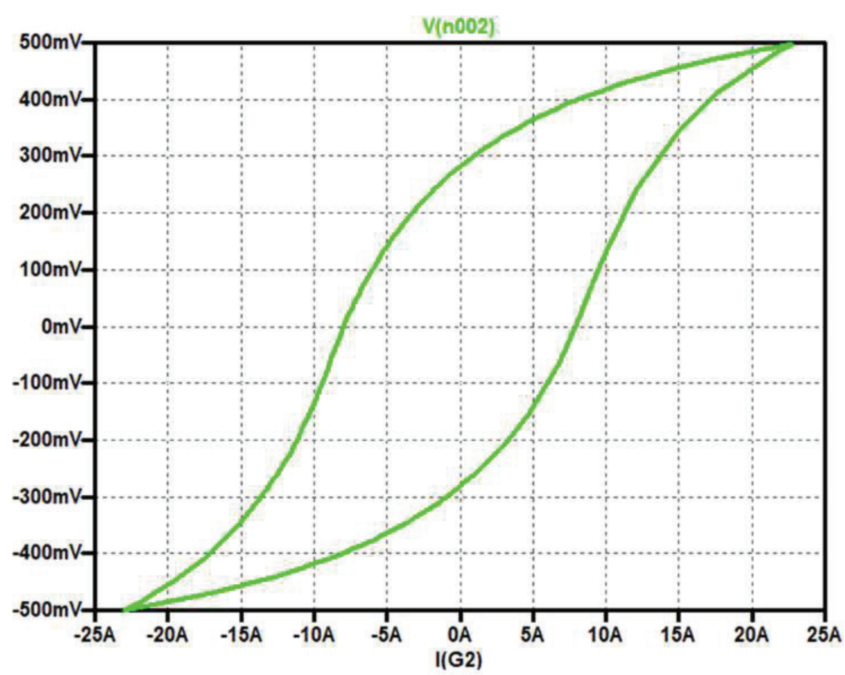


Fig. 3. Hysteresis loop for molypermalloy powder core

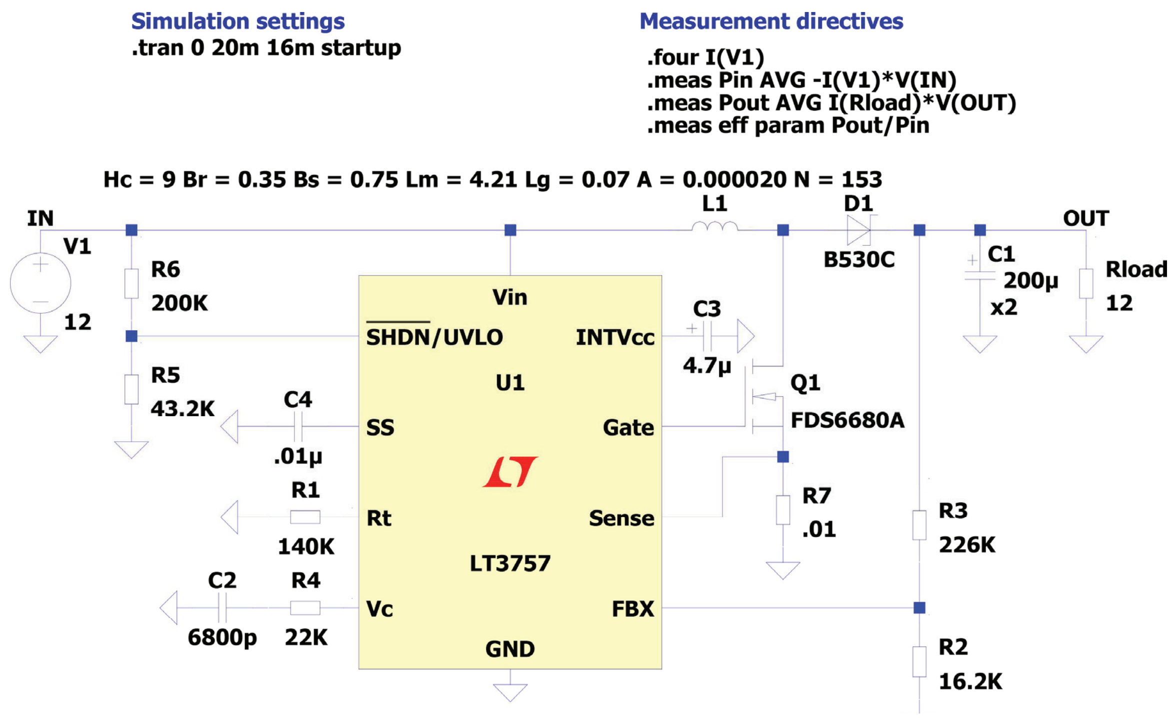


Fig. 4. Model of a boost converter with nonlinear inductance based on LT3757 controller

4. 2. Analysis of the influence of core cross-sectional area and air gap on interference level

The current spectrum of the input voltage source (conducted interference spectrum), for the given inductor and converter parameters, is shown in Fig. 5.

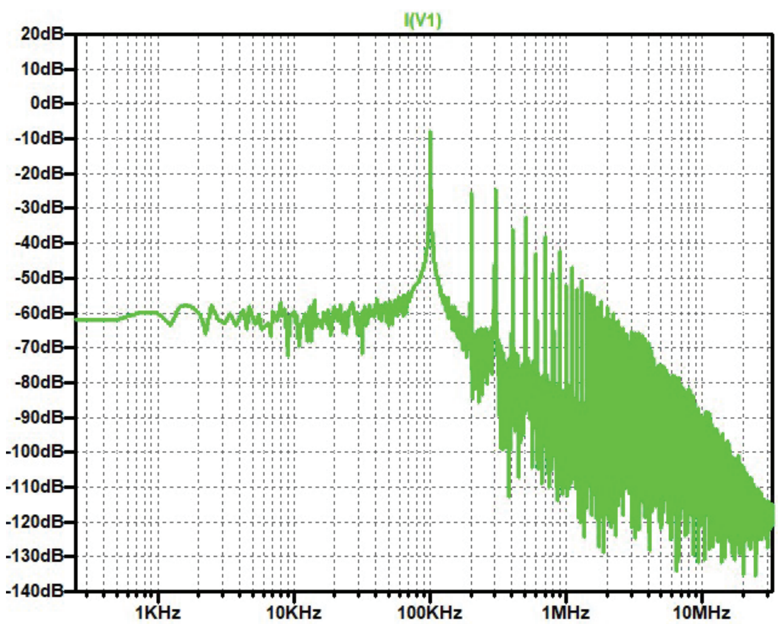


Fig. 5. Spectrum of the input current signal for the converter with nonlinear inductance and core cross-sectional area A=20 mm^2

To analyze the effect of inductor design parameters on electromagnetic interference (EMI), the cross-sectional area of the core was varied in the range from 2 to 80 mm^2. The results of interference spectrum measurement for the cross-sectional area of 2 and 60 mm^2 are shown in Fig. 6, 7, respectively. Table 1 shows the results of measuring the level of the first harmonic in the EMI spectrum and converter efficiency at different values of the core cross-sectional area.

A decrease in the cross-sectional area of the core leads to a decrease in the mass and dimensions of the converter, but at the same time leads to a decrease in efficiency and an increase in EMI level. An increase in cross-sectional area above the calculated value leads to a slight increase in efficiency and a significant decrease in the EMI level. Fig. 8 shows the graph of EMI level depending on the inductor core cross-sectional area.

Table 1

Results of the experiment on the effect of cross-sectional area on the level of generated interference

A*, mm^2	EFF, %	I_{AVG_L1}**, A	Level of the 1st harmonic of input current interference, dB
2	92.9	2.84	2.93
10	96.1	4.13	–2.1
20	96.7	4.15	–8.2
40	96.8	4.11	–14.1
60	96.9	4.12	–17.6
80	–	5	–21

* cross-sectional area
** average current through inductor L1

As follows from Fig. 8, an increase in the cross-sectional area of the core leads to a decrease in the level of the first harmonic of EMI. However, analysis of the spectrum with a cross-sectional area of 60 mm^2 shows that a subharmonic of a significant level with a frequency of 50 kHz appears in the spectrum.

This is because the converter goes into the mode of intermittent inductor current. The EMI spectrum of the converter with a core cross-sectional area of 60 mm^2 is shown in Fig. 9.

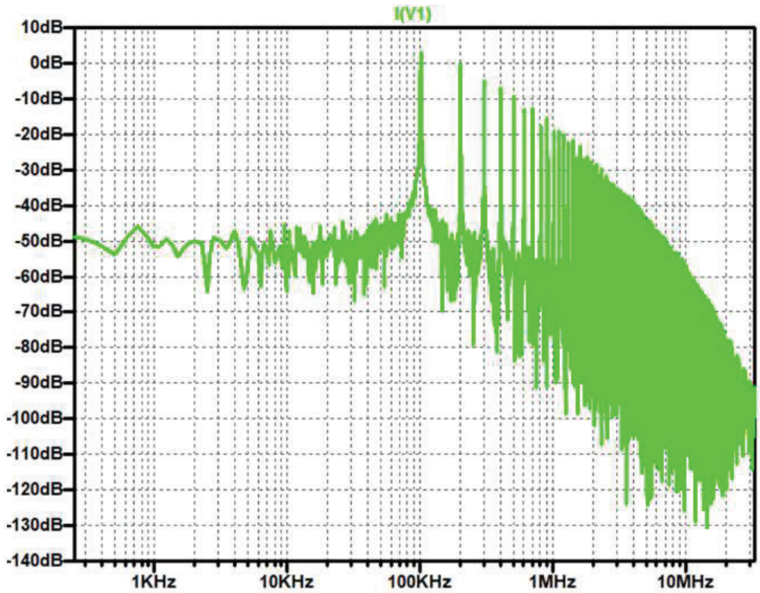


Fig. 6. Spectrum of the input current signal for the converter with nonlinear inductance and core cross-sectional area A=2 mm^2

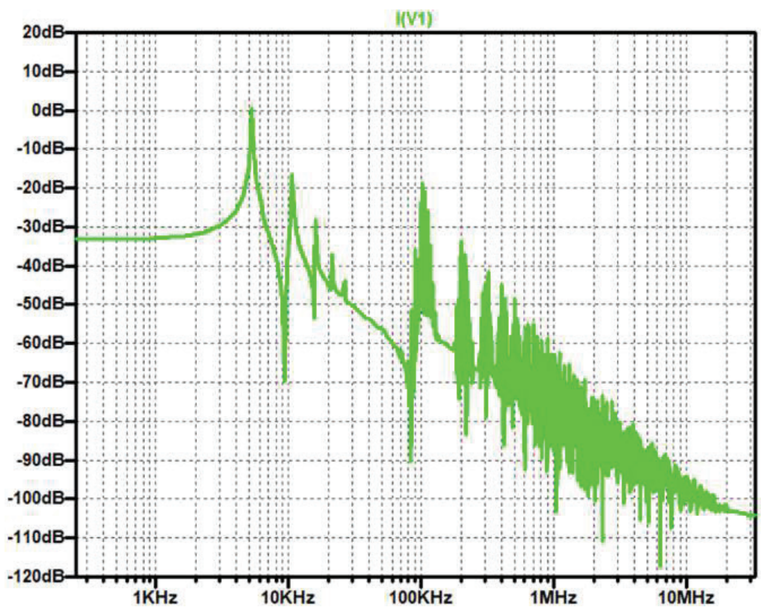


Fig. 7. Spectrum of the input current signal for the converter with nonlinear inductance and core cross-sectional area A=60 mm^2

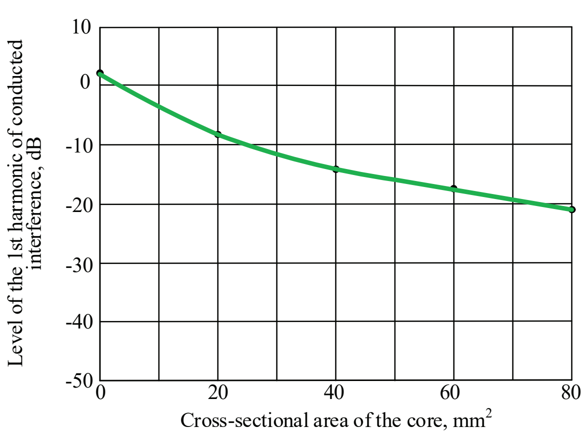


Fig. 8. Influence of the cross-sectional area of the core on the level of generated EMI

The analyzed converter operates in continuous mode, in which introducing an air gap into the core is recommended to prevent core saturation [10]. In previous experiments, the magnetic core had no air gap (L_g=0). The width of the air gap can be calculated by the formula:

$$L_g = \frac{I_{out\_\max} \cdot N}{B_{\max} \cdot 796} - \frac{L_m}{\mu} = \frac{2 \cdot 153}{0.525 \cdot 796} - \frac{42.1}{35{,}000} = 0.73 - 0.0012 \approx 0.72 \text{ mm}, \quad (16)$$

where I_{out_max} is the maximum output current of the converter, μ is the relative magnetic permeability of molypermalloy powder.

The results of studies of the converter with nonlinear inductance and air gap in the magnetic core are given in Table 2.

With the gap width of less than 0.45 mm, the converter goes into the intermittent mode and low-frequency components of a large level appear in the input current spectrum.

The average inductor current in all experiments was close to the saturation current. At a calculated gap width value of 0.7 mm, the continuous mode is maintained over the entire range of current variation.

Experimentally, a gap of 0.45 mm was determined to be optimal. With this gap width, the continuous operation of the converter is maintained (Fig. 10), minimum current ripple (less than 0.4 A) and high efficiency in the inductor are provided. Compared to an inductor without a gap, the gain in the converter EMI level is approximately 11 dB.

With an increase in the gap over 8 mm, the operating mode changes to intermittent and the inductor current for the duty cycle manages to drop to zero (Fig. 11). The input current spectra of the converter with a gap width of 0.45 mm and 8 mm are shown in Fig. 12.

Table 2

Results of the experiment on the effect of the width of the air gap in the core on the level of EMI generated by the converter

Gap width L_g, mm	Efficiency, %	Average inductor current, A	Level of the 1st harmonic of input current interference, dB
0.45	97.4	4.1	–19.7
0.5	96.9	4.1	–18.9
0.75	96.9	4.1	–16
1.0	96.9	4.1	–13.3
1.5	96.9	4.1	–9.1
2	96.9	4.1	–7.57
2.5	96.9	4.1	–5.6
3.0	96.9	4.1	–4.0

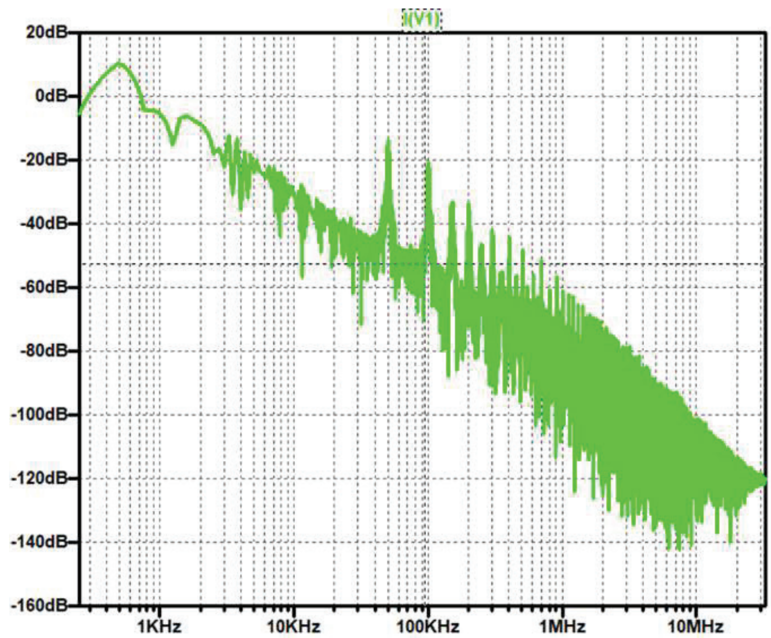


Fig. 9. Spectrum of the input current signal for the converter with nonlinear inductance and core cross-sectional area A=60 mm^2

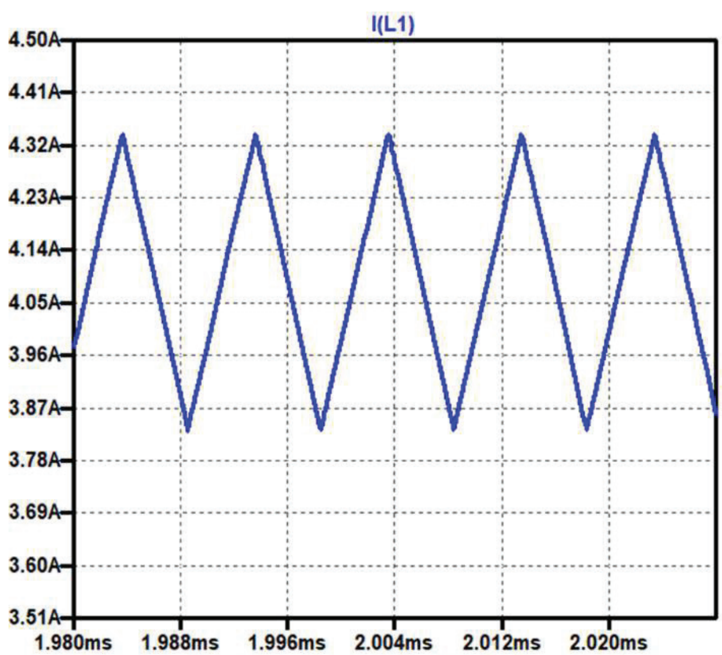


Fig. 10. Waveform of current through the inductor with an air gap width of 0.45 mm

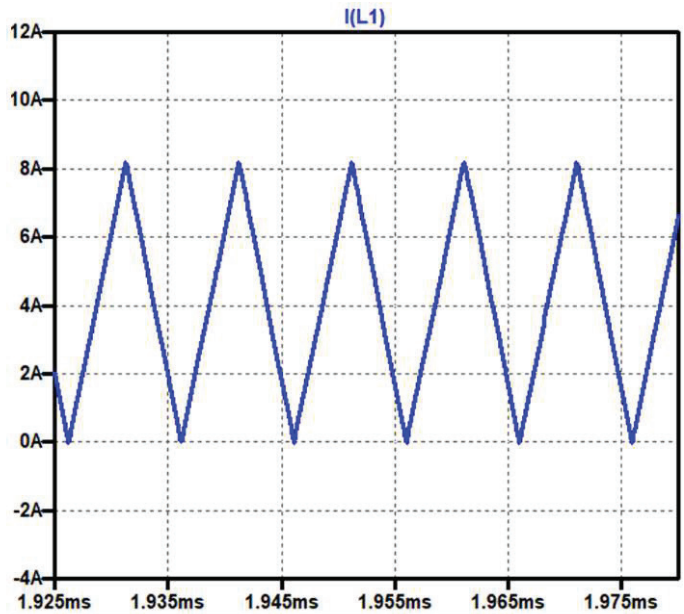
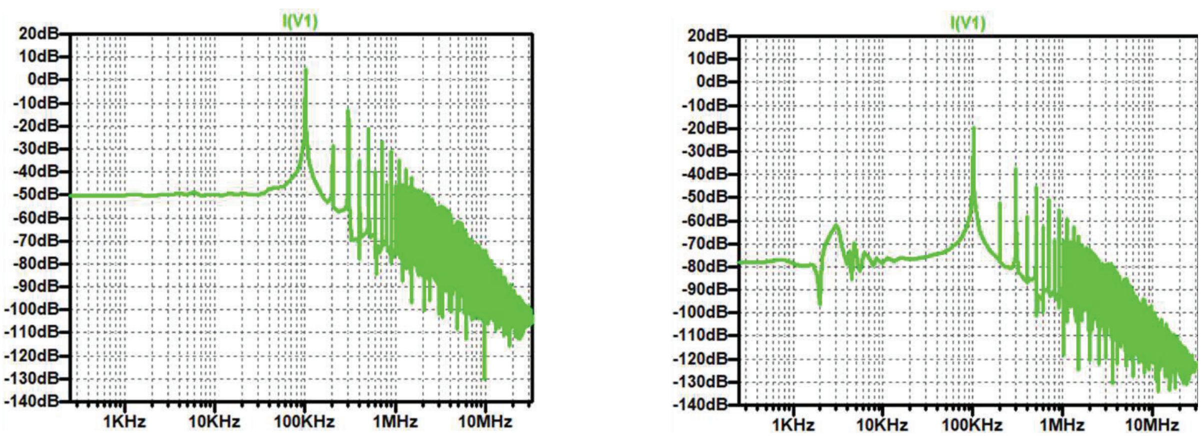


Fig. 11. Waveform of current through the inductor with an air gap width of 8 mm



a *b*

Fig. 12. Spectra of the converter input current at I_{OUT}=2 A: *a* – with an air gap width of 8 mm; *b* – with an air gap width of 0.45 mm

The experiments show the need to analyze the effect of the gap width on the EMI level.

4. 3. Analysis of the influence of core material on interference level

Table 3 shows the inductor design parameters needed to study converter models using different core materials, and Table 4 – results of the study of the converter EMI level.

Table 3

Chan model parameter values for different core materials

Material	N	B_r, T	A, cm^2	V_{min}, cm^3	B_s, T	L_m, cm	H_c, A/m
Molypermalloy powder (MPP)	153	0.35	0.2	0.86	0.75	4.21	9
Iron powder	66	0.15	0.074	0.13	1.4	1.699	45
Ferrite	50	0.1	0.3	0.63	0.5	2.1	14.3
Alsifer	136	0.15	0.2	0.87	1.05	4.21	1.76

All experiments were carried out with the same input and output parameters of the converter and without an air gap in the inductor core.

As follows from Table 4, the alsifer core provides the lowest interference level. Compared to the molypermalloy powder core, the gain is about 3 dB. Although all materials provide high efficiency values (more than 96 %), the alsifer core provides the highest value of this parameter.

Table 4

Results of the analysis of the influence of material type on EMI level

Material	Efficiency, %	Average inductor current, A	Level of the 1st harmonic of input current interference, dB
Molypermalloy powder (MPP)	96.4	4.11	–15.8
Iron powder)	96.1	4.13	–15.3
Ferrite	96.4	4.11	–17.0
Alsifer	96.5	4.11	–19.0

Introduction of an air gap of 0.2 mm into the alsifer core allows reducing the level of the 1st harmonic of input current interference to –23 dB (Fig. 13).

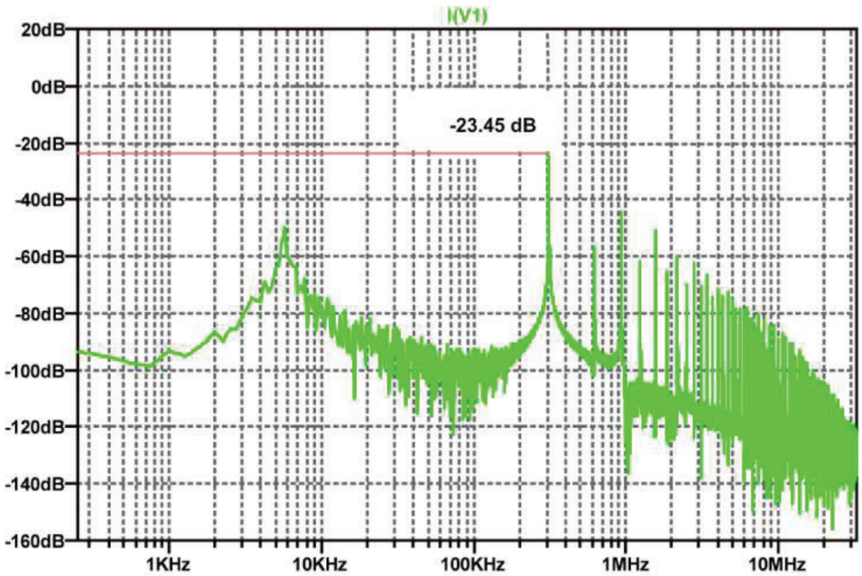


Fig. 13. Spectrum of the input current signal for the alsifer core with 0.2 mm gap width

As follows from the experiments, varying the width of the air gap in the inductor core of the DC/DC converter allows reducing the level of interference generated by the converter. Moreover, for different core materials, this value is usually different.

5. Discussion of the results of studying the effect of inductor design parameters on the level of electromagnetic interference

The models proposed in the work for studying the effect of design parameters on the level of electromagnetic interference generated by switching converters, shown in Fig. 1, 4, allow taking into account the nonlinearity of the magnetization characteristics of the core material to the level of electromagnetic interference.

The results obtained in this work are explained by the fact that when analyzing the electromagnetic interference generated by converters, the distortion of the waveform of current flowing through the power switch and the inductor is taken into account. The distortion of the current waveform is due to the non-linearity of the magnetization characteristic of the inductor core, as shown in Fig. 3. This phenomenon, in turn, leads to an increase in the level of EMI generated by the converter.

The obtained relationships between the level of electromagnetic interference and the cross-sectional area of the inductor magnetic core, presented in Fig. 5–7 and Table 1 show that an increase in core cross-sectional area leads to a decrease in EMI level. This is due to the fact that with an increased cross-sectional area of the magnetic core, the operating point shifts to the linear region of the magnetization characteristic. Knowing this relationship, it is possible to determine how much the core cross-sectional area should be increased in order to achieve a reduction in the EMI level by a given value. The results of analyzing the effect of the width of the air gap in the magnetic core on the EMI level given in Table 2 allow taking this parameter into account in the inductor design to minimize EMI at given converter parameters.

The results of analyzing the influence of the core material given in Table 4 make it possible to reasonably choose the core material not only in terms of frequency losses, but also minimum introduced interference. The choice of the optimum, in terms of EMI level, air gap width, as follows from Table 2 and Fig. 13, depends on the core material used. Different levels of interference generated by inductors with different core materials are due to different magnetization characteristics.

In the studies of other authors, the effect of the nonlinearity of the magnetization characteristics of the converter inductor on the level of generated EMI is not considered. These works mainly focused on the analysis of losses in inductors and transformers that occur during operation in near-saturation modes.

An attempt to analyze the effect of the core cross-sectional area on the EMI level is made in [1]. However, in this work, there was no constructive calculation of inductor with the given parameters, no analysis of the influence of the core material and air gap in it on the EMI level is carried out.

The proposed approach to analyzing converter operation allows for the calculation and modeling of converters with various parameters to optimize the parameters of a nonlinear inductor or transformer at the design stage. Such an analysis is not carried out in the works known to the authors.

Of course, the results obtained do not allow assessing all the factors affecting the EMI level of switched-mode power supplies. Therefore, work in this direction is advisable to continue. In the study, we did not analyze the operation of buck and universal buck/boost converters, which may have different dependences of interference level on their operating modes.

For a more complete understanding of the effect of the nonlinearity of the magnetization characteristics of inductor and transformer cores on the level of interference generated by switching converters, it is necessary to conduct research with other types of converters.

6. Conclusions

1. The proposed model of a converter with a nonlinear inductor makes it possible to study the level of conducted interference generated by DC/DC converters when the inductor design parameters and core material change. The model allows you to automatically calculate converter efficiency when changing the operating mode.

2. The experiments showed that saturation of the inductor core leads to an increase in the level of conducted interference generated by the converter. Moreover, these dependencies are different for different core materials.

The relationship between the level of generated conducted interference and the cross-sectional area of the inductor core is determined. It is shown that an increase in core cross-sectional area leads to a decrease in interference level and an increase in converter efficiency.

Analysis of the effect of the width of the air gap in the inductor core on the interference level showed that this relationship is nonlinear and different for different core materials. In addition, it is shown that the air gap width affects the operating mode of the converter. When using a core with an optimum air gap width (in terms of generated EMI), it is possible to decrease the interference level from 4.5 to 6 dB compared to an inductor without an air gap.

3. The relationship between the interference level and the converter core material at a given power switch frequency is determined. It is shown that the correct choice of the core material allows reducing the interference level due to this factor by about 3 dB.

The proposed research method makes it possible to calculate and simulate the operation of a switching voltage converter with specified input and output parameters. This approach allows determining optimum, in terms of generated interference, inductor parameters – magnetic core volume, core cross-sectional area and air gap width.

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