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THE DC-DC CONVERTERS EMI FILTERS CALCULATION METHOD USING LTspice

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The paper proposes a methodology for designing a filter for lowering conductive interference level, generated by pulse voltage converters. Not only the proposed method takes into account the requirements of the standard for electromagnetic compatibility, but also the parameters of the LISN node to measure the level of noise, which are given by a converter to a power supply chain. The articles describes the example of the filter design for a lowering DC-DC converter the noise level of which is in accordance with the standard CSPR25. All stages of design are illustrated by models, they are developed in the LTspice program. Models for analyzing the amplitude-frequency response of a interference filter loaded on a LISN are presented. It is shown that when modeling the operation of pulse sources, it is not advisable to use LISNs with the idealized characteristics of elements. The obtained filter calculations' results confirm the correctness of the proposed method. References 11, figures 9.

Keywords: electromagnetic noise, common mode and differential mode interference, filter electromagnetic noise, attenuation.

Introduction. In modern electronic devices, switching power supplies have become widespread, mainly due to high efficiency. However, the price for such efficiency is a creation of electromagnetic interference (EMI) by these kinds of power supplies. Interferences created by the operation of such suppliesare divided into radio interferences which spread as an electromagnetic field and conductive interferences, which are transmitted through wires. The conductive interferences are divided into common mode and differential mode interference [1].

There are various methods of reducing electromagnetic interference, but one of the most effective is the use of an EMI filter at the input of the pulse converter. In papers[2, 3, 4] there are examples of design of EMI filters in software packages LTpower CAD, NI Multisim, which allow automatic calculation and modeling of switching power supply with specified EMI filter, while meeting the requirements of different standards of electromagnetic compatibility. However, this design method can only be applied to power supplies built on the components of Analog Device, which are part of the base, the LTpower CAD program.

In paper [5] describes the method of EMC filter calculations for switching power supplies according to the CISPR22 standard. However, the proposed method does not show the influence of the parameters of the components Artificial Mains Network/Line Impedance Stabilization Network - (AMN/LISN), on the calculation of the EMI filter.

In paper [6], describes a method for designing a complex LLCL filter containing three inductors and one capacitor. Such a EMI filter is more complicated than single-link L or Pi filters and may not always be an acceptable solution due to its higher complexity and cost.

A universal method of designing EMI filter is proposed in paper [7] asan example of designing a filter for compliance with the CISPR16 standard. The method proposed by the authors takes into account the level of interference created by the converter without a filter. During the design of the filter, the margin is set by the attenuation introduced by it at the frequency of the first harmonic - 10 dB. The cutoff frequency of the filter is determined with the condition that the intensity of the frequency response decline is 40 dB/decade, then set the capacitance of the filter capacitor and calculate the inductance of its choke.

The aim of the work is to develop a methodology for designing EMI filters for DC-DC converters using the LTspice software package, which takes into account the parameters of AMN/LISN components.

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One of the objectives of the study is not only to create a methodology for the design of EMI filters, but also recommendations for modeling such devices to test the effectiveness of the designed EMI filter.

It is known that different standards of electromagnetic compatibility EMC use different AMN/LISN devices to measure the EMI level, which leads to differences in the input resistance of these devices in a wide range of frequencies. The classical theory of LC-filters assumes their calculations at a constant resistance of the signal source, which is equal to the load resistance. The difficulty of designing filters to reduce the level of electromagnetic interference is due to the fact that the filter is loaded with a complex resistance that varies over a wide range of frequencies, and the resistance of the source of interference also depends on the frequency.

Therefore, before designing a EMI filter, you need to consider the above factors.

Since the theoretical calculations of the level of EMI generated by switching power supplies are too complex and inefficient, it is possible to compare the noise levels of these converters with the help of simulation modeling, using simulators.

The LTspice program was chosen to simulate the operation of the EMI filter connected to a DC-DC converter, taking into account the imperfections of the characteristics of its passive components.

This paper proposes a method of filter design that takes into account the level of interference generated by DC-DC converters, the input resistance of the AMN/LISN node and the parameters of passive components. Since different AMN/LISNs with different topologies are used for different electromagnetic compatibility standards, it is necessary to determine the input resistance of this node at the preliminary design stage.

In the first stage, the AMN/LISN impedance is calculated, and then a low-pass filter with the same impedance is designed, taking into account the required attenuation at a given frequency.

Consider the process of determining the wave resistance AMN/LISN with the example of equipment that meets the CISPR standard 25 [8]. Fig. 1 shows a diagram of the connection of AMN/LISN to the power supply to measure the levels of EMI (which is analogous to the V-shaped equivalent of the network [9]) and verify compliance with the requirements of CISPR 25.

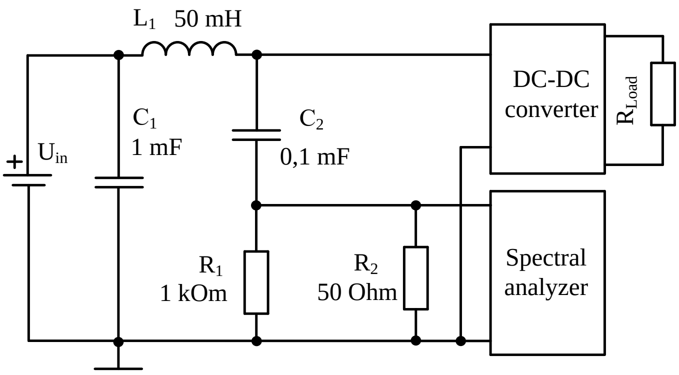

Fig. 1

This standard provides for the use of AMN/LISN with both a 5 μH inductor and a 50μH inductor when operating a DC-DC converter from a power supply. Consider the calculation procedure based on the requirements for devices of class 4 using a 50μH inductor.

The impedance of the AMN/LISN circuit is determined by the value of the capacitance of the capacitor C_1 and the inductance of the inductor L_1. In the calculations, the capacitance C_1 can be ignored due to the fact that in series with the capacitor included a resistor of 50 Ohms (input resistance of the spectrum analyzer). Capacitor C_2 with resistor R_2 form a high-pass filter with a cutoff frequency of 30 kHz. Therefore, the impedance of AMN/LISN can be calculated by the formula:

$$\rho = \sqrt{\frac{L_1}{C_1}} = \sqrt{\frac{50 \cdot 10^{-6}}{1 \cdot 10^{-6}}} = 7{,}1 \text{ Ohm}. \qquad (1)$$

To obtain detailed information about the parameters of LISN its frequency response is found in the scheme which is as close as possible to the actual mode of operation. Fig. 2. shows measured the amplitude-frequency response on the attenuation scheme.

Fig. 2 also shows the frequency response of the input DC voltage source V_{in} with an internal resistance of 0.1 Ohm to the capacitor C_1 and resistor R_3, (curve 2). It should be noted that the internal resistance of the source V_{in} does not affect the frequency response, but only affects the transmission factor from the test signal generator V_2 to the input voltage generator. Curve 1 indicates the frequency response of LISN, which is linear in the frequency range above 100 kHz.

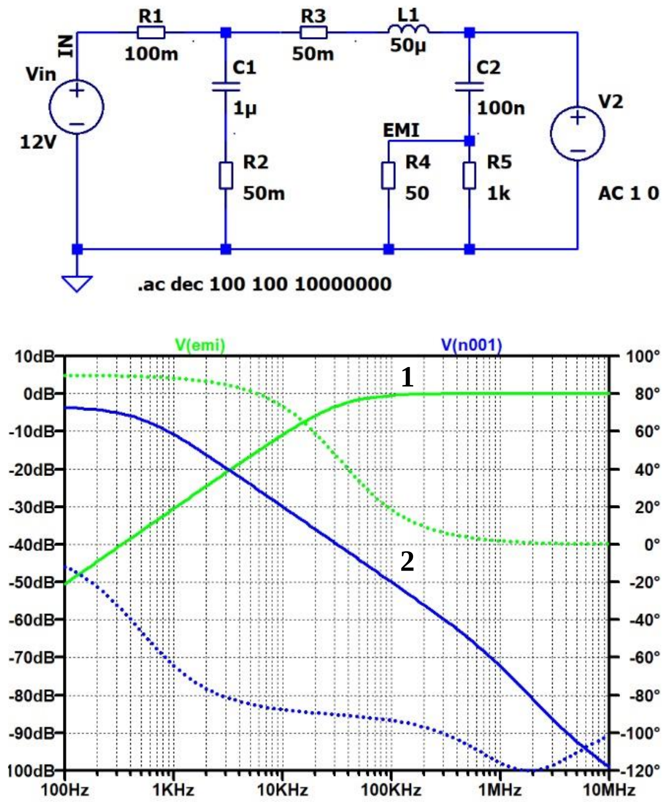

Fig. 2

From fig. 2 it follows that AMN/LISN for the input power supply is a low-pass filter with a cutoff frequency of 5 kHz and a frequency response decline of 20 dB/decade, and at the point of measurement of the interference spectrum high-pass filter with a cutoff frequency of 100 kHz.

At the second stage of design it is necessary to formulate requirements to the parameters of the EMC filter. To do this, you must either measure the noise level of the real converter, or simulate such a converter. Fig. 3 shows the model of the step-down DC-DC converter on the basis of the LTC7800 Analog Devices chip with the connection recommended by the manufacturer.

When modeling the circuit in LTspice, it should be noted that the spectrum is derived in dB and is calculated as the ratio of the root mean square values of the spectrum relative to level 1 V. Knowing the EMI levels in decibels, we can calculate the EMI level in the conventional dBµV ratio [10]. To do this, you need to convert the obtained values of the spectral components in µV, using a simple relationship:

$$U_{EMI}(B) = 10^{\frac{U_{EMI}(\mathrm{dB})}{20}}. \quad (2)$$

To recalculate the values obtained in (2) in dBµV it is necessary to perform the transformation:

$$U_{EMI}(\mathrm{dB\mu V}) = 20\lg\frac{U_{EMI}(\mathrm{V})}{1\cdot 10^{-6}\ \mathrm{V}}. \quad (3)$$

To automatically recalculate in dBµV, it is necessary to enter the divisor of 1 µV in the window of the noise spectrum display in Fig. 4.

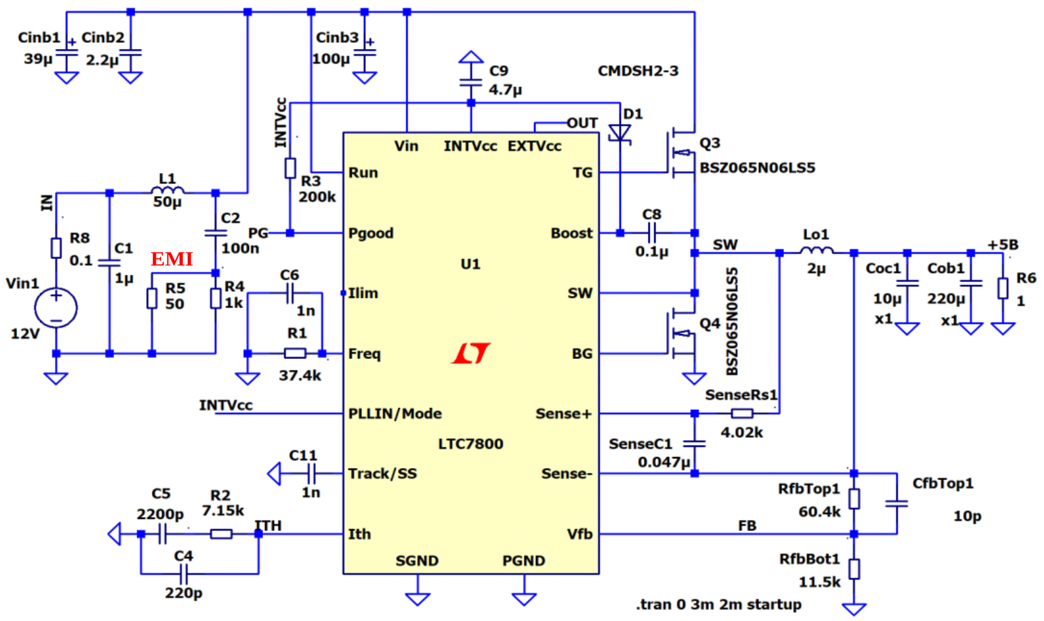

Fig. 3

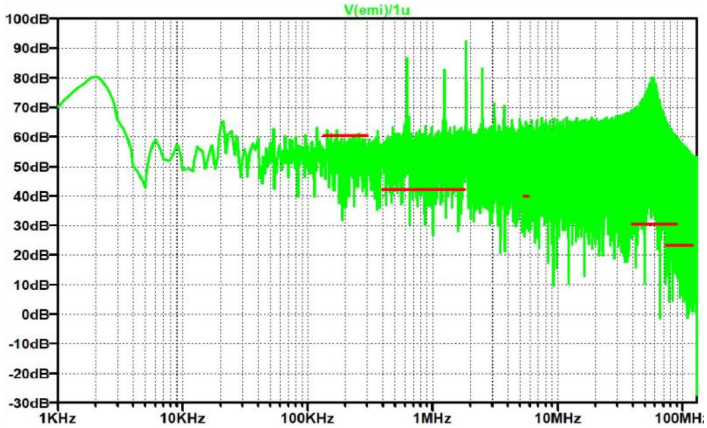

Fig. 4

In this figure, this is the value of V(emi)/1u, where *emi* is the designation of the point of the circuit at which the spectrum is measured. In fig. 4 this is the point to which resistor R_5 is connected. To increase the accuracy of the calculation of the simulation spectrum in LTspice was performed in an alternative mode.

The horizontal lines show the permissible noise levels according to the CISPR25 standard for Class 4 devices. For the spectral component with a frequency of 600 kHz (switching frequency of the power switches of the converter) the noise level is 87 dBμV. This value exceeds the value allowed by the CISPR25 standard in the frequency range 0.5… 2 MHz by 45 dB. The obtained value of the frequency response makes it possible to formulate requirements for the required level of applied attenuation for the EMI filter, it is necessary to provide a attenuation margin of at least 3 dB. As can be seen in Fig. 4 the EMI filter must provide attenuation at a frequency of 600 kHz not less than 48 dB.

The next step in the LTspice program is to determine the rate of decline of the frequency response of a single-link LC-filter, taking into account that it is loaded on the input resistance AMN/LISN.

Since at a frequency of 600 kHz the low-pass filter must make attenuation not less than 48 dB, the cutoff frequency of the filter is calculated by the formula:

$$f_c \geq f_1 / 10^{\frac{A_{sum}}{20}} = 600 \cdot 10^3 / 10^{\frac{48}{20}} = 600 \cdot 10^3 / 1122 = 2389 \text{ Hz}, \quad (4)$$

where f_1 is the frequency of the switching transistors, A_{sum} – the required attenuation of the filter at the frequency of the first harmonic of the noise.

Knowing the wave resistance of AMN/LISN, you can proceed to the calculations of the EMI filter elements values. Now we express the inductance of the filter through the impedance, using relation (1).

$$L_f = \rho^2 C_f , \quad (5)$$

where L_f, C_f are the inductance and capacitance of the filter, ρ is the impedance.

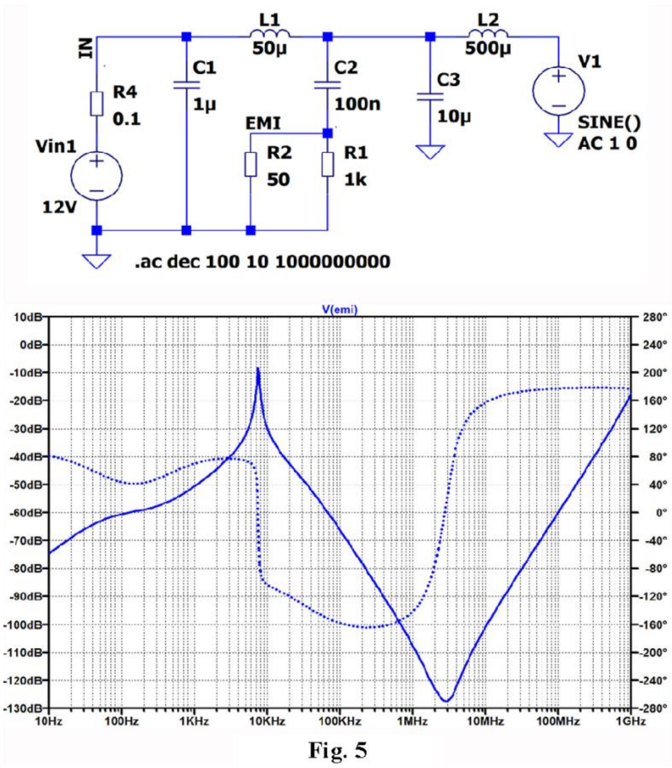

Fig. 5

The expression 5 shows how to obtain the required value of the capacity of C_f:

$$C_f = \frac{1}{2\pi f_c \rho}. \quad (6)$$

Putting the frequency value of f_c = 2,39 kHz to the above expression (6) from expression 4 we obtain:

$$C_f \geq \frac{1}{2\pi \cdot 2390 \cdot 7 \cdot 1} \geq 9,38 \cdot 10^{-6} \text{ F}.$$

Rounding the value of C_f to 10 μF, you can find the value of inductance L_f:

$$L_f \geq \rho^2 C_f = 7,1^2 \cdot 10 \cdot 10^{-6} \geq 0,5 \text{ μH}. \quad (7)$$

The model for the analysis of the frequency response of the filter loaded on AMN/LISN, and the frequency response measured at the EMI point are shown in Fig. 5. The following components were selected for the filter design: Wurth Electronik L_2 inductor with *Rser* = 0.007 Ohm, 8000 Ohm parallel resistance and 10 pF interwinding capacitance, Wurth Electronik capacitor with equivalent series resistance 0.0026 Ohm and lead

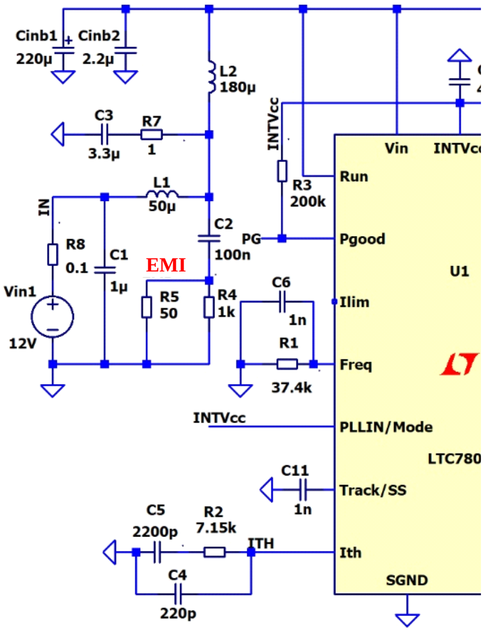

Fig. 6

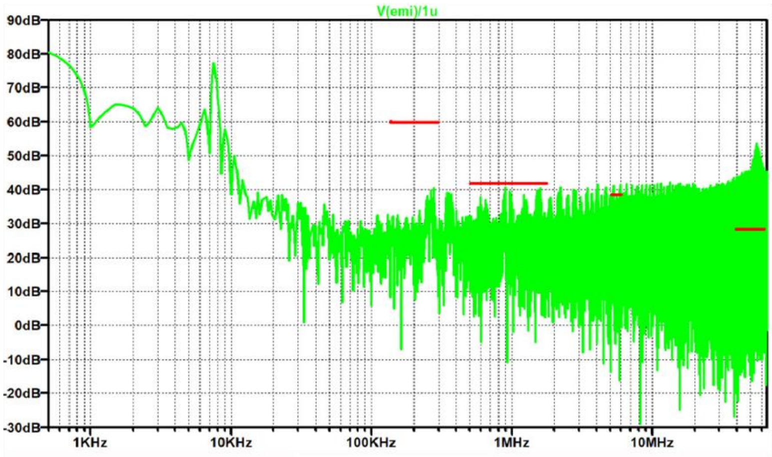

Fig. 7

inductance 0.8 nH.

The model with the EMC filter connected at the input, consisting of elements L_2, C_3 and R_7, is shown in Fig. 6, and the spectrum of noise - in Fig. 7 (the right part of the DC-DC converter circuit remained unchanged and corresponds to the circuit in Fig.3). Since the quality factor of the oscillatory circuit formed by L_2, C_3 is very high, as shown in Fig. 5, so to reduce it the resistor R_7 was added. In the absence of this resistor, an emission in the interference spectrum will be observed at a resonance frequency of this circuit of 13.8 kHz.

To correctly calculate the interference spectrum, it is necessary to set the start time of the signal analysis at the point marked on the diagram as EMI, after the completion of transients in the circuit. To do this, the LTspice program first sets the analysis start time to zero and the analysis end time to 10-20 ms (depending on the circuit parameters). The simulation directive looks like this **.tran 0 10m startup**. After displaying the process schedule, there is a visual time to complete the transition process and this time fits into the analysis directive. For the model shown in Figure 6, the transient completion time is approximately 7.5 ms and the analysis directive takes the form **.tran 0 10m 8mstartup.**

In the interference spectrum of the converter with the filter connected, the level of the first harmonic with a frequency of 600 kHz is 36 dBmkV, which is below the permissible level of 42 dBmkV according to the CISP25 standard for this frequency.

But the spectral components with frequencies above 2 MHz significantly exceed the allowable levels of EMI. From fig. 5 it follows that the attenuation of the filter consisting of L_2 and C_3, starting from the frequency of 3 MHz decreases rapidly, because the parasitic capacitance of the windings of the inductor L_2 forms a high-pass filter with input resistance AMN/LISN. To attenuate the high-frequency components in the interference spectrum, it is necessary to add another link of the low-pass filter, which has a much higher cutoff frequency than the first link.

Analyzing the spectra in Fig. 7 and fig. 5 it can be concluded that the second link of the EMI filter should make attenuation at a frequency of 90 MHz not less than 34 dB, and taking into account the margin of 3 dB - 37 dB.

The cutoff frequency of the second link of the filter f_{c2} can be found according to formula (4) above:

$$f_{c2} \geq f_2 / 10^{\frac{A_{sum}}{20}} = 90 \cdot 10^6 / 10^{\frac{37}{20}} = 1.3 \cdot 10^6 \ Hz,$$

The calculation of the second link of the filter is similar to the calculation of the first. Since the AMN/LISN impedance and the impedance of the calculated filter link are the same, a 7.1 Ohm impedance is also used to calculate the second filter link.

Calculate the capacitance of the capacitor of the second link of the filter:

$$C_{f2} \geq \frac{1}{2\pi \cdot 1{,}3 \cdot 10^6 \cdot 7{,}1} \geq 17{,}25 \cdot 10^{-9} F.$$

Assuming the value of C_f = 18 nF, you can find the value of inductance

$$L_{f2} \geq \rho^2 C_F = 7{,}1^2 \cdot 18 \cdot 10^{-9} \geq 0.9 \ \mu H.$$

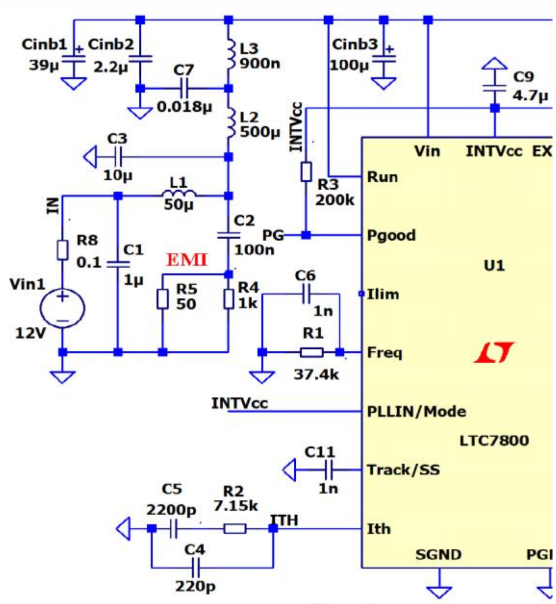

Fig. 8

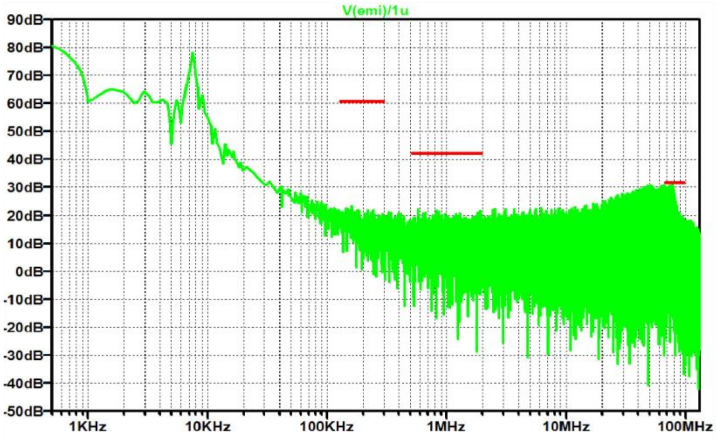

Fig. 9

The model of the EMI filter, consisting of two links - L_3, C_7 and L_2, C_3, is shown at the left part of Fig. 8 (the right part of the DC-DC converter circuit remained unchanged and corresponds to the circuit of Fig.3). To implement the second link of the filter, a Coilcraft 900 nH inductor with a resistance of *Rser* = 0.008 Ohm and a parallel resistance of 84.78 Ohm was selected, and a capacitor from Wurth Electronik with an equivalent series resistance of 0.116 Ohm and a terminal inductance of 5.659 nH was used as a capacitor.

The results of measuring the interference spectrum are shown in Fig. 9. And although now the noise levels meet the requirements of the standard in the field of high frequencies, when calculating the filter it is necessary to make a margin for attenuation of 6…10 dB.

Based on the results of the experiments, we can formulate a method of designing a noise filter for DC-DC converter in the software package LTspic:

1. Measure the interference spectrum of the DC-DC converter (experimentally or by simulation). If the switching frequency of the transistor (s) may change during the operation of the converter, the measurement should be performed at the lowest switching frequency.

2. Determine the frequency and amplitude of the component of the spectrum with the maximum level.

3. If the noise spectrum is measured by electronic modeling, we recalculate the levels from dB to dBmkV according to the formula:

$$U_{EMI}(f_{\max.ampl.}) = 20\lg\frac{10^{\frac{U_{EMI}(dB)}{20}}}{1\cdot 10^{-6}V}[dB\mu V],$$

де $f_{\text{max.ampl.}}$ is the component in the spectrum of the noises with the maximum amplitude.

4. Determine the required input attenuation of the EMI filter at the frequency $f_{\text{max.ampl.}}$

$$A_{\text{sum.}}(dB\mu V) = U_{\text{EMI}} - U_{CISPR},$$

where U_{CISPR} is the permissible value of the interference level at the frequency $f_{\text{max.ampl.}}$ according to the selected CISPR.

5. Find the cutoff frequency of the filter (f_c) EMC (single-link L - like LC - filter), given that the rate of decline of the frequency response of such a link, loaded on AMN/LISN, is approximately 34-36 dB/decade.

6. Determine the AMN/LISN impedance for the selected CISPR standard according to the formula $\rho = \sqrt{L_1/C_1}[Ohm]$, where L_1 is the inductance of the AMN/LISN choke, C_1 is the capacitance of the AMN/LISN capacitor connected in parallel to the input voltage source.

7.Calculate the value of the filter capacity by the formula $C_{\text{f}} = 1/(2\pi f_c \rho)$. Choose a capacitor with the required operating voltage not less than the maximum input voltage of the converter.

8. Calculate the value of the inductor of the filter according to the formula $L_{\text{f}} \geq \rho^2 C_{\text{f}}$. Choose an inductor with a maximum allowable peak current of at least $1.2I_{\text{in.ampl.}}$. Where $I_{\text{in.ampl}}$ - amplitude of the input current of the converter. In series with the filter capacitor include a resistor, the resistance of which may be

in the range of 0.2… 2 Ohm and depends on the resistance of the losses of the inductor and the filter capacitor.

9. Experimentally or by simulation find the resistance value of the resistor connected in series with the filter capacitor to obtain the required attenuation.

When calculating the filter elements, it is desirable to know the resistance of losses in thechoke and capacitors AMN/LISN, because they have different values at different maximum currents for which AMN/LISN is designed. Not all AMN/LISN manufacturers provide these values. For example, in [10] the schematic diagram of AMN/LISN with achoke inductance of 5 μH, but no data on the resistance of thechoke. In [11] the value of the resistance connected in series with the capacitor C_1 AMN/LISN, but no data on the resistance of thechoke AMN/LISN. Although the influence of parameters (loss resistance) of these elements on the results of calculations has little effect.

Conclusions.

1. For the first time a method of designing an EMI filter is proposed, which takes into account the peculiarities of the construction of AMN/LISN nodes.

2. Analysis of the operation of the EMI filter with the software package LTspice showed that the level of attenuation of conductive interference is significantly affected by the quality factor of the LC filter link. It is shown how to determine the value of the resistance of the resistor to reduce the quality factor LC of the filter link by analyzing the noise spectrum in the presence of a filter.

3. When modeling the operation of a switching power supply, it is first necessary to determine the transient time to form the correct parameters of the modeling directive. If the spectrum analysis is performed before the end of the transient process, it will lead to the appearance in the spectrum of interference by a low-frequency component due to the resonance frequency of the circuit formed by inductors and filter capacitor in AMN/LISN.

4. The results obtained in the modeling process confirmed the accuracy of the proposed method of filter design.

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УДК 621.314

МЕТОДИКА РОЗРАХУНКУ ПРОТИЗАВАДНИХ ФІЛЬТРІВ DC/DC-ПЕРЕТВОРЮВАЧІВ ЗА ДОПОМОГОЮ ПРОГРАМИ LTspic

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У роботі наведено методику проектування протизавадного фільтра для зниження рівня кондуктивних завад, створюваних під час роботи імпульсних перетворювачів напруги, за допомогою програмного пакета LTspic. Методика враховує не тільки вимоги стандартів з електромагнітній сумісності, але й параметри еквівалента мережі. Розглянуто приклад проектування протизавадного фільтра для понижувального DC/DC - перетворювача рівень завад якого відповідає стандарту CISPR25. Усі етапи проектування ілюстровано моделями, розробленими в програмі LTspice. Наведено моделі для аналізу амплітудно-частотної характеристики протизавадного фільтра, навантаженого на еквівалент мережі ЕМ (AMN/LISN). Показано вплив паразитних параметрів компонентів на розрахунок протизавадного фільтра. Під час розрахунку протизавадного фільтра отримано результати, які підтверджують правильність запропонованої методики. Бібл. 11, рис. 9.

Ключові слова: електромагнітна завада (ЕМЗ), симетрична завада, несиметрична завада, фільтр ЕМЗ, загасання.

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