IMPROVING EMI ATTENUATION IN FREQUENCY MODULATED POWER CONVERTERS

ELEKTROMAGNĒTISKO TRAUCĒJUMU UZLABOŠANA FREKVENČU MODULĒTOS IMPULSU PĀRVEIDOTĀJOS

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Keywords: boost converter, frequency modulation, amplitude modulation, EMI attenuation, input current

Abstract - The effect of frequency modulation on a power switching converter electromagnetic interference (EMI) attenuation is examined in this paper. A method known as "modified sawtooth" is applied for EMI attenuation in a boost converter and it is optimized in such a way to reduce EMI more effectively. The method is also verified experimentally by the use of a low power boost converter controlled via an arbitrary waveform generator. EMI attenuation up to 15 dB is achieved after using modified sawtooth modulating waveform.

Introduction

Electromagnetic interference (EMI) emission is always one of the major problems in the field of switching power converters (SPC) [1]. Various EMI reduction schemes have been proposed over the last decades [4,5]. The traditional techniques for mitigating the problems in SPC usually include the use of input EMI filters, shielding, proper design of printed circuit boards, soft switching techniques, etc [2]. Another successful approach for EMI reduction is based on modulating a parameter, such as the switching frequency in random or periodic manner [4]. As a result of this method, energy of discrete harmonics of unmodulated switching frequency is spread over a wider frequency range, thus significantly reducing peak EMI levels [2].
Despite the fact that random switching frequency modulation (SFM) is often used in many practical SPC because of better conducted EMI attenuation, periodic SFM have some advantages [2]. The problem with random methods is that EMI is equally spread along the whole frequency spectrum, i.e. such methods do not provide any control on the bands where EMI energy is spread, while periodic SFM do [2]. This feature is very important for certain applications such as cellular phones or automobile communications systems, where EMI at certain selective frequencies must be avoided [2]. That is why periodic SFM is chosen to be used in this paper.
Input current amplitude modulation (AM) effects caused by frequency modulation are the major problem worsening attenuation of conducted EMI in frequency modulated DC-DC SPC [3] and electronic ballasts [10]. Although the method known as "modified ramp" was used to minimize AM effects in electronic ballasts [10], this method, first of all, is not applied to boost converters; secondly, it is not optimized for given values of modulation parameters to reduce EMI more effectively. So the main aim of the paper is, firstly, to analyze effect of FM on the boost converter EMI attenuation, secondly, to verify if this method is effective for EMI reduction in boost converters, and finally, to optimize this method for maximum EMI attenuation considering FM parameters.

Theoretical analysis

Theoretical attenuation of modulated input current

The boost DC-DC converter in Fig.1 is used for the analysis. Since discontinuous conduction mode (DCM) is less preferable for the boost converter (mainly due to worse EMI) [5], all the

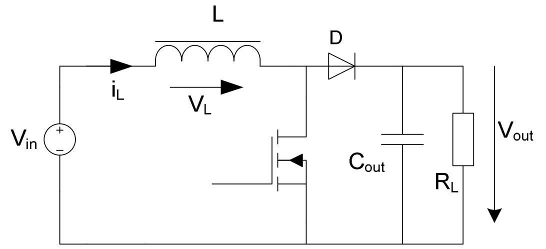

Fig.1 Basic schematics of the boost converter

calculations will be performed for continuous conduction mode (CCM). For the EMI performance of SPC the input current is of special interest, because it is responsible for conducted EMI. Therefore, the input current will be considered in this analysis.

For the boost converter inductor current i_L is equal to the input current. A basic equation for the inductor current is given by:

$$L\frac{di_L(t)}{dt} = V_L(t) \quad , \qquad (1)$$

where V_L is the voltage across the inductor L.

It is obvious that the inductor current from (1) is given by:

$$i_L(t) = I_L(0) + \frac{1}{L}\int_0^t V_L(t)dt \qquad (2)$$

Fig.2 shows the corresponding waveforms for the inductor voltage and current. Directly from (2), peak-to-peak inductor current ripples Δi_L over one switching period T_{sw} can be calculated as follows [5]:

$$\Delta i_L = \frac{V_{in}}{L} DT_{sw} \quad , \qquad (3)$$

where D is duty cycle.

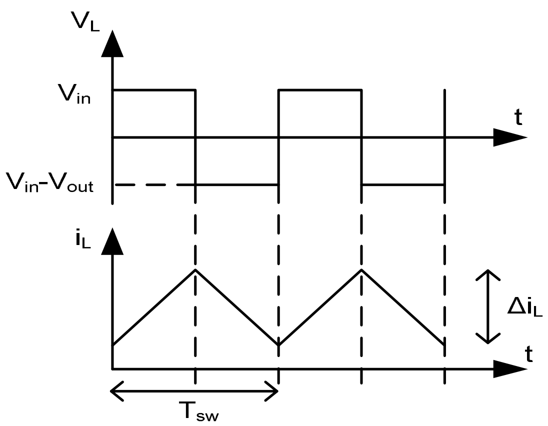

Fig.2 Theoretical unmodulated inductor current and voltage

Unmodulated inductor voltage spectrum of the converter consists of harmonics of switching frequency f_{sw}. When modulating the switching frequency, each individual harmonic is spread into a certain frequency band, thus reducing the peak amplitudes of EMI spectrum [2,6] (see Fig.3). Resulting spectrum consists of sidebands that are symmetrical with respect to each unmodulated f_{sw} harmonic [6,8]. Furthermore, the sidebands consist of side frequencies, which are modulating frequency (f_m) apart [4].

The worst situation for the boost converter from EMI point of view is when D=0.5, because all energy is concentrated in odd harmonics, so peak value is maximum [2,7].

A general expression of frequency modulated inductor voltage for D=0.5 is as follows:

$$s_m(t) = V_{in}\,\mathrm{sgn}[\cos(2\pi f_{sw}t + \theta(t))], \qquad (4)$$

where $\theta(t)$ is time dependent phase angle, according to [6]

$$\theta(t) = 2\pi\int_0^t k_f \cdot m(\tau)d\tau\,, \qquad (5)$$

where $m(\tau)$ is a modulating waveform; k_f is the scaling coefficient of the frequency deviation Δf_{sw} at given amplitude A_m of a modulating waveform, $k_f = \Delta f_{sw} / A_m$.

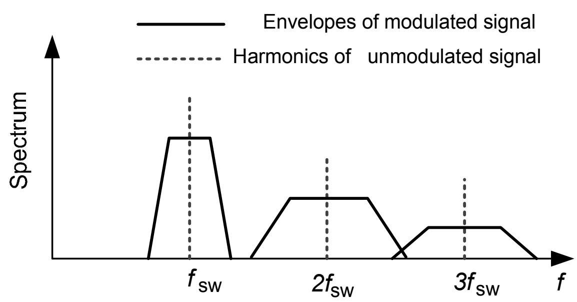

Fig. 3 Simplified spectral structure of modulated and unmodulated inductor voltage

Suppression of high-order harmonics is more effective than low-order ones, so the fundamental harmonic attenuation is worse than that for other harmonics of f_{sw} [4]. That is why we will consider only the attenuation of the fundamental harmonic. The attenuation (A) is the difference expressed in dB between maximum values of the unmodulated and modulated spectrum amplitude and is given by [8, 9]:

$$A = 20\log_{10}\left(\frac{\max(|S_{unmod}(f)|)}{\max(|S_{mod}(f)|)}\right), \qquad (6)$$

where $S_{unmod}(f)$ is the spectrum of unmodulated signal; $S_{mod}(f)$ is the spectrum of modulated signal. In present analysis, sawtooth modulating waveform (Fig.4) is used, because of its better EMI reduction potential compared with other waveforms, such as sinusoidal [8]. In order to get theoretical spectra for both modulated and unmodulated V_L and i_L numerical calculations in Matlab 7.5 are performed. Fig.5 depicts the calculated spectrum of frequency modulated

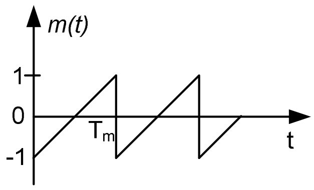

Fig.4 Sawtooth modulating waveform

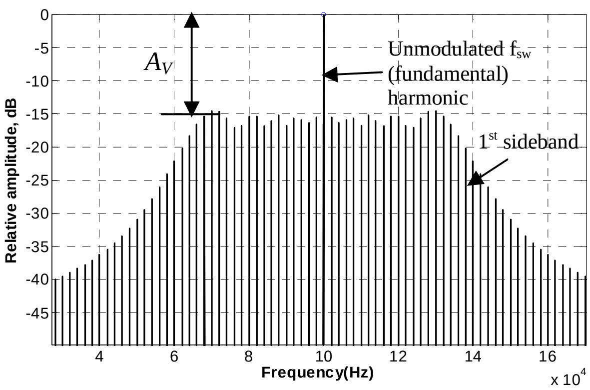

Fig.5 Theoretical spectrum of modulated V_L (the 1st sideband only shown). Modulation parameters: Δf_{sw}=40kHz, f_m=2kHz, f_{sw}=100kHz

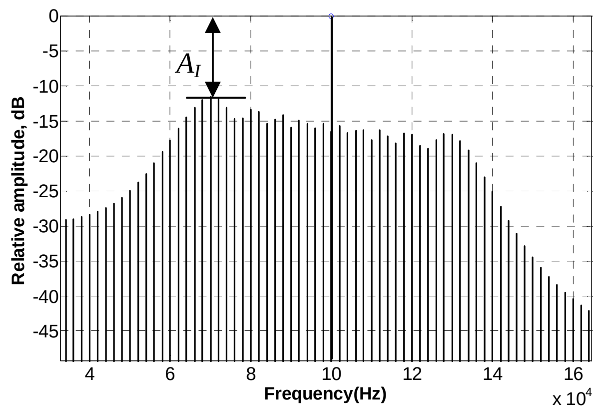

Fig.6 Theoretical spectrum of modulated i_L (the 1st sideband only shown). Modulation parameters: Δf_{sw}=40kHz, f_m=2kHz, f_{sw}=100kHz

inductor voltage in relative values with respect to fundamental harmonic amplitude of unmodulated V_L. The spectrum amplitude reduction for V_L is derived as follows:

$$A_V = 20\log_{10}(C_{1un\,modV} / C_{\max V}(f_{\max})), \qquad (7)$$

where $C_{1umnodV}$ is the fundamental harmonic amplitude for unmodulated inductor voltage; $C_{maxV}(f_{max})$ is the maximum amplitude of the harmonic of the 1st sideband at frequency f_{max}.

Theoretical spectrum of i_L (Fig.6) can be calculated using spectrum of V_L and (2) as follows:

$$|S_{\mathrm{mod}\,I}(f)| = |S_{\mathrm{mod}\,V}(f)|/(2\pi fL), \qquad (8)$$

where $S_{modI}(f)$ is modulated inductor current spectrum; $S_{modV}(f)$ is modulated inductor voltage spectrum. The theoretical attenuation A_I of maximum amplitude of unmodulated i_L spectrum is calculated using Matlab by the following expression:

$$A_I = 20\log_{10}\left(\frac{\max|S_{un\,\mathrm{mod}\,I}(f)|}{\max|S_{\mathrm{mod}\,I}(f)|)}\right), \qquad (9)$$

where $S_{unmodI}(f)$ and $S_{modI}(f)$ are unmodulated and modulated inductor current spectrum respectively. As a result, in Fig.7 the theoretical

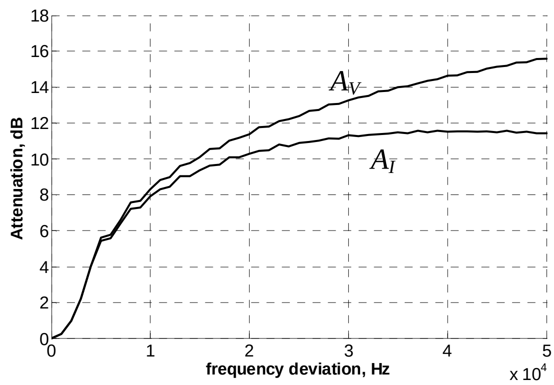

Fig.7 Theoretical A_I and A_V as a function of Δf_{sw} for f_m=2 kHz

attenuation as a function of Δf_{sw} with f_m=2kHz is shown for both V_L and i_L. As we can see from this figure attenuation of maximum amplitude of V_L spectrum is increasing function of Δf_{sw}. However, it is not the case for i_L: A_I increases when changing Δf_{sw} up to 30 kHz, then it becomes almost constant and after Δf_{sw} =45kHz it decreases slightly. The difference between A_V and A_I is caused by amplitude modulation (AM) of the input current. The reason for AM effects is that inductor current ripples Δi_L are inversely proportional to switching frequency according to (3). In the frequency domain, AM effects result in spectrum distortion characterized by the spectrum asymmetry with respect to central switching frequency [10]. As a result, more energy is concentrated in the lower half of the sideband [10]. Despite the fact that for small Δf_{sw} AM effects are not pronounced appreciably, they must be reduced, because the higher Δf_{sw} is, the higher attenuation is.

Improving EMI attenuation

Analysis of Fig.5 and Fig.6 can give important information to minimize AM effects and improve the attenuation. Since more energy is concentrated in the lower half of the sideband of modulated input current spectrum, one should decrease length of time spent by modulating waveform in frequency range below the central switching frequency [10]. This can be done by using different slopes of modified sawtooth modulating waveform (Fig.8) for the lower and upper halves

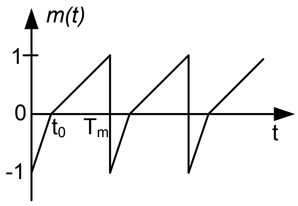

Fig.8 Modified sawtooth modulating waveform

of the sideband [10]. The slopes are controlled by changing values of t_0.

Despite the modified sawtooth is used also in [10] to reduce AM effects in electronic ballasts, there is no information how to choose t_0 for optimum EMI attenuation taking in account FM parameters. In order to find the optimum values of t_0 to get the best attenuation, numerical calculations in Matlab are again performed for the different values of f_m, Δf_{sw} (in the range 0 – 50 kHz) and t_0 (in the range $0.2T_m$ – $0.5T_m$). As a result, A_I as a function of both Δf_{sw} and t_0 for f_m=2kHz is depicted in Fig.9 using Matlab mesh function. A_I as a function of t_0 for different f_m but fixed Δf_{sw}=40kHz is shown in Fig.10. Analysis of the figures can reveal some interesting facts. Firstly, the higher Δf_{sw} is, the lower t_0 should be to minimize AM effects appreciably.

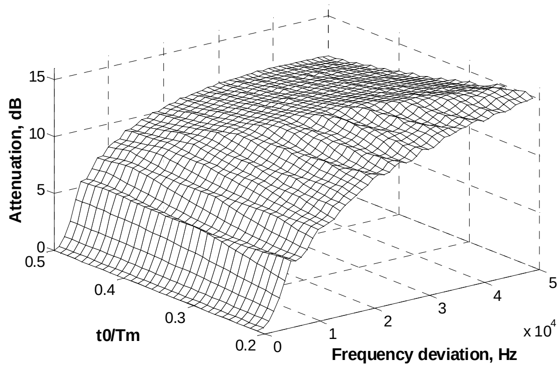

Fig.9 Theoretical A_I as a function of Δf_{sw} and t_0 for f_m=2 kHz

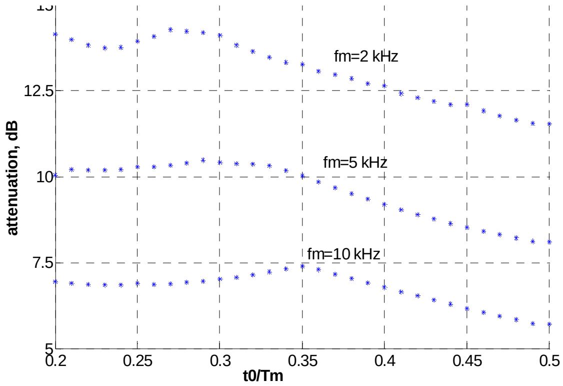

Fig.10 Theoretical A_I as a function of f_m and t_0 for Δf_{sw} =40 kHz

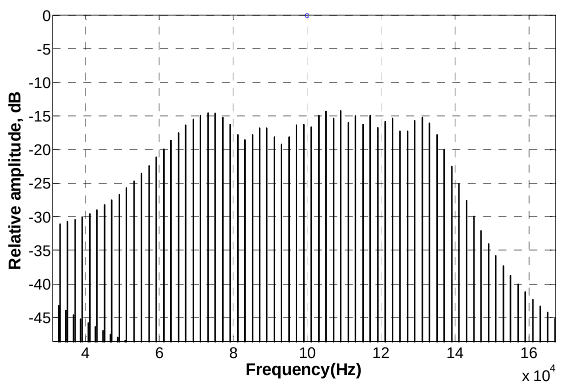

Fig.11 Theoretical spectrum of modulated i_L with modified modulating sawtooth waveform. Modulation parameters: Δf_{sw}=40kHz, f_m=2kHz f_{sw}=100kHz, t_0=0.27T_m

As it can be deduced from Fig.9 we can get 3.76 dB higher attenuation with optimum t_0 at Δf_{sw}=50kHz compared with unmodified sawtooth modulating waveform (with t_0=0.5T_m). Secondly, the higher f_m is, the lower difference between t_0 and 0.5T_m should be.

Optimum values of t_0 for a given Δf_{sw} and f_m can be found from those curves or using our Matlab code. The optimum values of t_0 give us a possibility to achieve the best attenuation drastically reducing AM effects. After applying optimum t_0, the spectrum of modulated i_L becomes more symmetrical with respect to the central switching frequency, as it is also shown in Fig.11.

Experimental verifications

Experimental setup

A frequency-modulated low power boost converter (Fig.12) is designed and built to test the theoretical calculations described above. The converter operating in CCM is tested in open loop mode. The input voltage of 5V is fed from a regulated DC source. Output resistive load is R_L=12Ω. The nominal output voltage V_{out}=8V at D=0.5. The nominal switching frequency f_{sw}=100 kHz.

To perform the frequency modulation, frequency modulated square waveform from an arbitrary waveform generator is fed into driver controlling the power MOSFET. All the modulation parameters, including t_0, can be set by the generator.

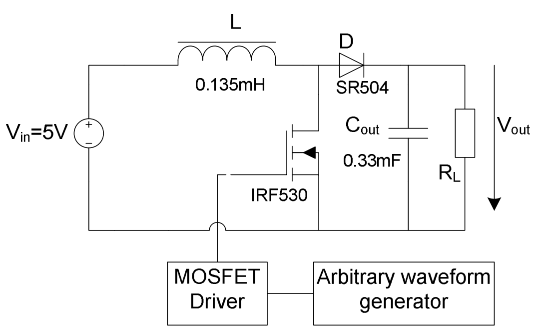

Fig.12 Simplified schematic diagram of the experimental setup

Experimental results

Input current ripples are analyzed by the use of a spectrum analyzer (Agilent E4402B) with RBW=200Hz. The experimental inductor current spectrum for f_m=2kHz, Δf_{sw}=40kHz and optimum t_0=0.27 is shown in Fig.13. Attenuation A_I of maximum amplitude of unmodulated i_L spectrum both experimental and theoretical as a function of Δf_{sw} for modified and unmodified sawtooth modulating waveform is depicted in Fig.14.

To achieve the best attenuation theoretically obtained optimum values of t_0 were used in our experiments. The comparison of the results prove that experimental results are in close agreement with the theoretical calculations.

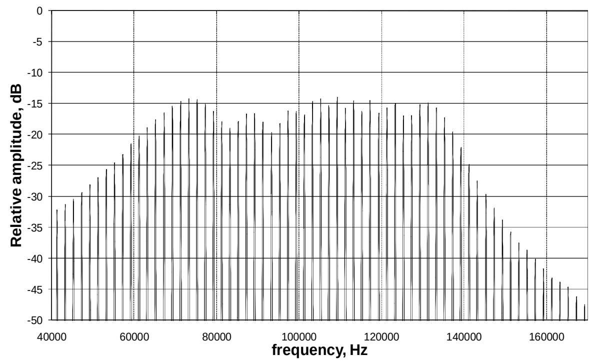

Fig.13 Experimental spectrum of modulated i_L with modified modulating sawtooth waveform. Modulation parameters: Δf_{sw}=40 kHz, f_m=2 kHz, f_{sw}=100 kHz, t_0=0.27T_m

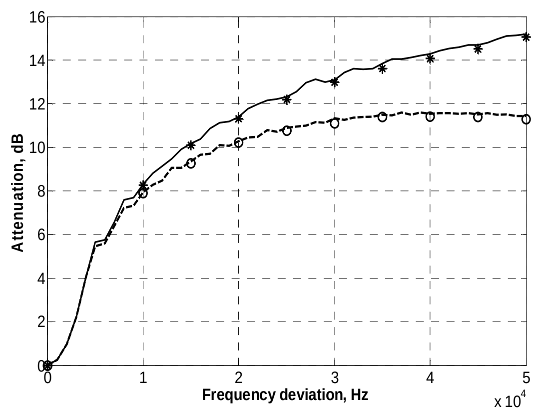

Fig.14 Theoretical and experimental A_I as a function of Δf_{sw} for f_m=2 kHz. (Solid line: theoretical A_I for modified sawtooth with optimum t_0; dashed line: theoretical A_I for unmodified sawtooth with t_0=0.5T_m ; (*) experimental A_I for modified sawtooth with optimum t_0; (o) experimental A_I for unmodified sawtooth with t_0=0.5T_m)

Conclusions

Analysis of the spectrum of frequency modulated boost converter input current causing conducted EMI has been presented in this paper. The analysis is based on theoretical calculations of spectra of modulated and unmodulated inductor current and attenuation of maximum spectrum amplitude of unmodulated one. During the analysis it was found out that the main reason for worsening the attenuation with increasing switching frequency deviation are amplitude modulation effects inherent in the input current of the boost converter. The amplitude modulation effects can be effectively neutralized by the modification of the modulating waveform, leading to reduction in the input current spectrum distortion and improvement of the attenuation. The theoretical calculations have been verified experimentally showing the attenuation up to 15 dB with modified modulating waveform.

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He is currently the IEEE member.

D. Stepins. Improving EMI attenuation in frequency modulated power converters

The effect of frequency modulation on a power switching converter electromagnetic interference (EMI) attenuation is examined in this paper. A method known as "modified ramp" is applied for EMI reduction in boost converters and it is optimized in such a way to reduce EMI more effectively. The method is based on the use of a modified sawtooth modulating waveform with different slopes for the lower and upper halves of the frequency-modulation-generated sidebands. The usefulness of the method for boost converters is also verified experimentally by the use of a low power boost converter operating in continuous conduction mode and controlled via an arbitrary waveform generator. EMI attenuation up to 15 dB is achieved after using the modified sawtooth modulating waveform with optimum values of a parameter t_0 controlling the slopes. Analysis of the results shows that the experiments are in a close agreement with the theoretical calculations. The optimum values of t_0 are calculated using numerical analysis of EMI spectrum taking into account amplitude modulation effects. Influence of frequency modulation parameters on t_0 is also discussed.

D. Stepins. Elektromagnētisko traucējumu uzlabošana frekvenču modulētos impulsu pārveidotājos

Šajā darbā tiek izpētīta frekvenču modulācijas ietekme uz impulsu pārveidotāju elektromagnētisko traucējumu (EMT) vājinājumu. Metode zināma kā „lauztais zaģis" pielietotā boost pārveidotājā EMT samazināšanai un ir optimizēta efektīvakai EMT samazināšanai. Šī metode ir balstīta uz lauzta zagveida modulācijas signāla pieleitošanas. Šim modulācijas signālam ir dažādie stāvumi sānjoslu kreisajai un labai daļām. Šīs metodes efektivitāte boost pārveidotājos ir arī pārbaudīta eksperimentāli izmantojot mazas jaudas paaugstinošo impulsu pārveidotāju vadāmo no signāla geņeratora. 15 dB EMT vājinājums bija sasniegts izmantojot šo metodi ar optimālām parametra t_0 vērtībām, kurš kontrolē stāvumu. Iegūto rezultātu analīze parada, ka eksperimentālie rezultāti labi sakrīt ar teorētiskiem. Optimālas t_0 vērtības ir aprēķinātas izmatojot EMT spektra skaitlisko analīzi ņemot vērā amplitūdas modulācijas efektus. Frekvenču modulācijas parametru ietekme uz t_0 ir arī apskatīta.

Д. Степин. Улучшение ослабления электро-магнитных помех в импульсных преобразователях с модуляцией частоты комутации

В данной работе исследуется влияние частотной модуляции на электромагнитные помехи (ЭМП) в импульсных преобразователях электрической энергии. Метод основанный на ломанном пилообразном сигнале применен для ослабления ЭМП в повышающем преобразователе (ПП) и оптимизирован для более эфективного ослабления ЭМП. Этот метод основан на использовании пилообразного модулирующего колебания, имеющего разную крутизну для левой и правой половины боковых полос. Эффективность данного метода в ПП также проверена экспериментально, используя повышающий импульсный преобразователь малой мощности. Ослабление ЭМП в 15 дБ было достигнуто, при использовании пилообразного модулирующего колебания с оптимальными значениями параметра t_0 регулирующего крутизну. Анализ полученных результатов показал, что эксперименты сходятся с теоретическими вычислениями..