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IMPACT OF SIGNAL DISTORTION IN A POWER AMPLIFIER ON TELECOMMUNICATION SYSTEM EFFICIENCY

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Abstract. The need to increase information transfer rate in up-to-date telecommunication systems led to a wide spread of OFDM and SEFDM signals with a relatively high peak-to-average power ratio. In case of power amplifiers operating at a fixed supply voltage, this power ratio feature can result in up to 20–30 % decrease in efficiency, which predetermined the interest in the use of more efficient solutions. These methods, including envelope tracking, outphasing, etc., are based on non-linear transformations of a radio frequency signal and/or its envelope. The resulting signal distortions can be accompanied by a noticeable increase in error rate at the receiver, which negatively affects the telecommunication system performance. The paper considers a set of factors with the most significant impact upon signal distortion in a power amplifier with tracking supply. An analytical model of a multi-cell tracking power supply was developed taking into account the errors of envelope and reference voltage digital conversion, the transistors' inertial parameters, the nonlinearities of the magnitude- and phase-frequency responses of the output low-pass filter. The impact of these factors on the envelope signal spectrum distortion and the bit error rate at receiver were considered. Proceeding from the results obtained, the authors proposed requirements to the transistors switching performance and the permissible dispersion of the parameters of envelope tracking power supply.

Keywords: modulated power supply, harmonic distortion, envelope tracking, power amplifier, efficiency, analytical model

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ВЛИЯНИЕ ИСКАЖЕНИЙ СИГНАЛОВ В УСИЛИТЕЛЕ МОЩНОСТИ НА ЭФФЕКТИВНОСТЬ СИСТЕМЫ ПЕРЕДАЧИ СООБЩЕНИЙ

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Аннотация. В современных телекоммуникационных системах, исходя из необходимости повышения скорости передачи информации, широко используются многочастотные сигналы (OFDM и SEFDM), для которых характерен сравнительно высокий пик-фактор. Последнее обстоятельство в случае усилителей мощности, работающих при фиксированном напряжении питания, может привести к снижению КПД до 20–30 % и предопределило интерес к использованию более эффективных в плане энергетической эффективности технических решений. В их число входят методы следящего питания, дефазирования и другие, основанные на нелинейных преобразованиях радиочастотного сигнала и/или его огибающей. Возникающие при этом искажения сигналов могут сопровождаться заметным возрастанием количества ошибок на приемной стороне, что негативно отразится на эффективности системы передачи сообщений. В статье рассмотрены основные факторы, оказывающие наиболее существенное влияние на уровень искажений сигналов в усилителе мощности, реализованном на основе метода следящего питания. Разработана аналитическая модель многоячейкового модуляционного источника питания, учитывающая погрешности дискретизации сигнала огибающей и опорного напряжения, инерционные параметры транзисторов, нелинейности амплитудно-частотной и фазо-частотной характеристик выходного фильтра нижних частот и проведена оценка степени их влияния на искажения спектра сигнала огибающей и вероятность битовой ошибки при приеме радиосигналов. На основе полученных результатов сформулированы требования к быстродействию транзисторов и допустимому разбросу параметров модуляционного источника питания.

Ключевые слова: модуляционный источник питания, нелинейные искажения, метод следящего питания, усилитель мощности, КПД, аналитическая модель

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Introduction

The use of multi-frequency signals (OFDM and SEFDM) is one of the promising ways to increase the information transfer rate in telecommunication systems (TS) [1]. However, the insufficient bandwidth of the telecommunication channel, as well as the linearity disturbance of its transfer characteristic, usually lead to signal distortions, which can be accompanied by a noticeable increase in the number of errors arising at the receiver and thus reducing the TS efficiency.

The paper proposes a universal approach that allows to evaluate the effect of signal distortion, regardless of which part of the telecommunication channel (transmitter, communications line or receiver) they occur. Within the limited size of the paper, the case is considered when distortions occur only in one section of the channel – in transmitter and, accordingly, the main contribution to the signals parasitic change is made by the power amplifier (PA).

When amplifying multi-frequency signals with power amplifiers (PAs) operating in the classes AB or B, which are considered to be sufficiently linear, the relatively high peak to average power ratio (PAPR) of this type of signals leads to a decrease in efficiency as far as 20–30 %. This circumstance predetermined interest in the use of technical solutions that are more efficient in terms of power efficiency. Among the common ways to keep the efficiency of the PA at an acceptable level, it should be noted the methods of envelope tracking (ET) [2–5], envelope extraction and restoration (EER) [3, 6, 7], outphasing [3, 8–10] and Doherty [3, 11, 12]. At the same time in the first two methods pulse-width modulation (PWM) is used to amplify the envelope signal, during which, as is known, the signal is subjected to nonlinear transformations, and in the second method, in addition, the switch mode is also used to amplify the radio frequency signal, which can also be accompanied by distortions. Nonlinear distortions are also inherent in the other two known methods of amplifying signals with a high PAPR.

Taking into account the above, the purpose of the paper is to determine the parameters of the PAs which have the most significant impact on the signal distortions and caused by these distortions the bit error rate in the receiver. Solving this problem will make it possible to recommend the most rational requirements in terms of transmitter implementation.

Initial provisions

Let's consider the main criteria that will be used in assessing the influence of signal distortions on the efficiency of the TS.

As is known, any change in signals' spectrum is a very accurate indicator of undesirable distortions that have occurred in them. However, it is important not only to take into account the level of spurious spectral components, but also in what part of the spectrum they appeared. In particular, parasitic spectral components caused by the use of PWM in ET power supplies can be grouped around harmonics of the clock frequency, which is as high as ten or more times compared with the upper frequency in the signal spectrum [13].

Accordingly, these spectral components, although they can be considered as a measure for assessing the distortions that have arisen in the signal, but taking into account their influence is more interesting from the point of view of the problems that will be encountered in ensuring electromagnetic compatibility (EMC) requirements in the transmitter. So when evaluating the TS efficiency, the most interesting are those parasitic spectral components that directly occur into the frequency band of the useful signal, and, accordingly, can lead to errors in receiver.

In order to simultaneously take into account both the disposition of spurious spectral components in the frequency band of the signal as well as their level, it is advisable to use a universal scalar indicator, which can be chosen as the bit error rate. This characteristic accumulates all the negative effects caused by signal distortions. Based on the above reasoning, we will divide the solution of the problem under consideration into two stages: at first, we estimate the influence of various PA parameters on the signal distortion, then we determine the bit error rate due to these distortions.

Transmitter model

When getting on to the discussion of the transmitter model, in order to unambiguously determine it, it is necessary to specify the method that is supposed to be used to amplify signals with a high PAPR. In this regard, for definiteness, we will consider the ET method. The block diagram of the output stage of the transmitter, is shown in Fig. 1. One more clarification should be made here: since a detailed simultaneous consideration of the processes in the ET power amplifier and in the RF power amplifier can be quite voluminous and beyond the scope of one publication, we will assume that the effect of distortions introduced by the RF power amplifier can be neglected. Several reasons can be cited to justify this approach. One of the arguments is that the problem of lowering signal distortions in RF power amplifiers is not new, and currently there are effective solutions to reduce them by introducing pre-distortion into the

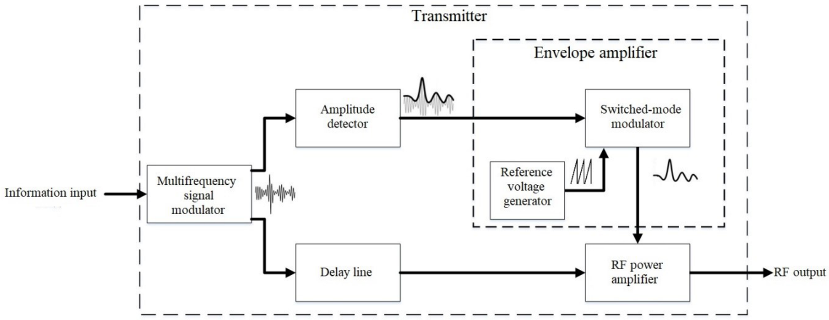


Fig. 1. The structure of transmitter output stage

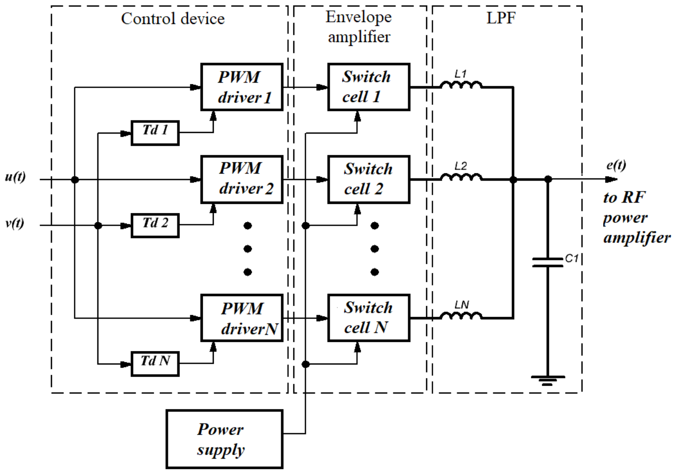


Fig. 2. Structure of a multi-cell modulated power supply

amplified signal [14–20]. In contrast, the study of the main factors that lead to envelope distortions in ET power supplies has not been adequately reflected in the known publications. Moreover, in those few publications that are devoted to this problem, the authors limit themselves to only considering distortions in the ET power amplifiers, without touching on the problem of how these distortions will affect in the TS efficiency lowering when receiving signals. And finally, taking into account the contribution that ET power sources can make to increasing the level of bit errors is also relevant due to ever-increasing requirements for expanding their bandwidth, which in itself is a non-trivial task and may be accompanied by signal distortions increase.

To expand the bandwidth of modulated power supplies (MPS), they are usually performed on the basis of a multi-cell structure, the diagram of which is shown in Fig. 2. In it, individual cells of the MPS are implemented in the form of half-bridge circuits that amplify the envelope voltage in PWM mode [4, 5].

In Fig. 2 the following designations are used: $u(t)$ – envelope voltage; $v(t)$ – reference sawtooth voltage used in PWM; $e(t)$ – output voltage. Herewith the time delay of the reference voltage for the i-th cell ($i = 1, 2, ..., N$) is equal , where T_r – the period of the reference voltage $v(t)$, N – the number of cells. The distortions caused by the ET power amplifier can be conditionally divided into three types, depending on in which part of the voltage spectrum $e(t)$ they appear.

Distortions of the first type are caused by nonlinear transformations of the voltage $u(t)$ during PWM and appear as a set of spectral components around the frequency $f \approx kF_{\max}qN$ (region III in Fig. 3), where $F_{\max}$ – the upper limit of the frequency band in the voltage $u(t)$ spectrum, q is the ratio of the reference

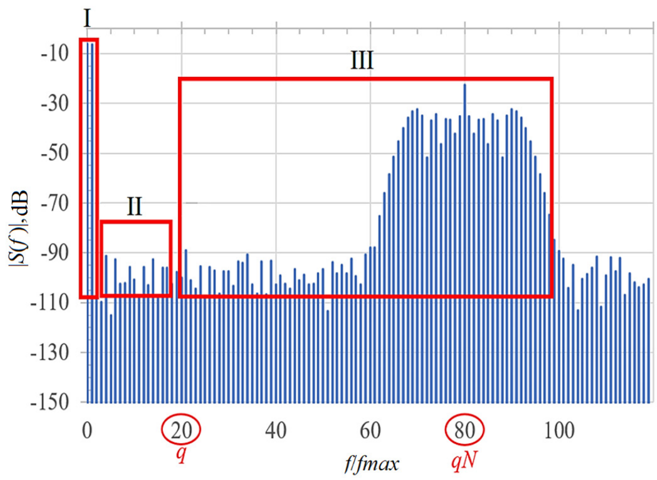


Fig. 3. Typical regions in the output voltage spectrum of a multicell MPS

voltage frequency to F_{max}, $k = 1, 2, \ldots$ – an integer. The negative impact of these spectral components can be reduced by increasing the frequency of the reference voltage and the number of cells N at a fixed bandwidth of the low-pass filter.

Distortions of the second type can be classified by the appearance of spurious spectral components in the region $F_{max} < f < F_{max}qN$ (region II in Fig. 3), which theoretically should be absent when using a multicell structure. However, studies have shown that the cause of these distortions, as a rule, is an error in setting the phases of the reference voltage in the channels of a multi-cell MPS, as well as the inductance dispersion of the coils used in the output circuits of the cells [13, 21, 22]. Spurious spectral components at the bottom of this region need to be controlled as they can get through the lowpass filter into the RF signal.

The most undesirable referring to the impact on the TS efficiency are distortions of the third type, which are accompanied by the appearance of spurious spectral components in the frequency range $f < F_{max}$ occupied by the envelope signal (region I in Fig. 3). These spectral components cannot be eliminated by filtering neither in the MPS itself nor at the output of the RF amplifier. The most noticeable contribution to the appearance of these distortions is made by:

1) envelope signal and reference voltage sampling errors;
2) inertial parameters of transistors (difference in rise and fall times in each of the switches) [21, 22];
3) turn-on and turn-off time intervals dispersion of the MPS transistors;
4) nonlinearity of the amplitude-frequency and phase-frequency characteristics of the MPS low-pass filter, and what is more the influence of both nonlinearities can increase significantly if the cutoff frequency is incorrectly chosen.

The most obvious way to take into account in the transmitter model listed above points 1–4 is simulation using CAD software. However, in the case of an MPS with an extended bandwidth, which is usually achieved by increasing N, the number of transistors in the model also increases ($2N$). As a result, the time required for one simulation iteration with a certain set of parameters increases markedly. In the case of a large number of combinations of variable parameters and, especially when studying the influence of the spread of transistor parameters (see Section 3), when the number of calculation iterations will be determined by the required fiducial probability and can reach tens for each combination of variable parameters, such simulation will become difficult to implement.

An alternative approach that makes it possible to overcome the problems noted above is the use of an analytical model [13], in which, under certain assumptions, it is possible to significantly reduce the time spent on calculations.

When creating an analytical model, we will rely on the well-known expression that describes the N-cell MPS output voltage, which was obtained under the assumption that transistors are ideal:

$$e(t,\ q,\ N)=\frac{1}{2N}\sum_{i=1}^{N}\left[1+\operatorname{sign}\left(u(t)-\mathrm{v}(i,\ t,\ q)\right)\right], \tag{1}$$

where $\mathrm{v}(t, m, q)$ – the sawtooth reference voltage; t – time; i – cell number.

In this form, the model makes it possible to adequately estimate only the spectral components that are multiples of the product qN (region III, Fig. 3).

In order to take into account the influence of errors that arise when using the digital representation of the envelope voltage and the reference voltage (see Section 1), the original model should be converted to the following form:

$$\begin{gathered} e_d\left(\tau_d,\ q,\ N,\ n_d,\ K_p\right)= \\ =\frac{1}{2N}\sum_{k=0}^{\infty}\sum_{i=1}^{N}\left\{1+\operatorname{sign}\left[\frac{\operatorname{floor}\left[u(k\tau_d)2^{n_d}\right]}{2^{n_d}}-\frac{\operatorname{floor}\left[\mathrm{v}(i,\ k\tau_d,\ q)K_p\right]}{K_p}\right]\right\}, \end{gathered} \tag{2}$$

where τ_d – sampling time; n_d – is the capacity of the analog-to-digital converter (ADC); floor(x) – a function that rounds each element x to the nearest integer less than or equal to this element; K_p – number of quantization levels of reference voltage.

If it is necessary to consider the influence of the inertial properties of transistors (point 2), as well as the uneven gain-frequency characteristic and nonlinearity of the phase-frequency characteristic of the low-pass filter (point 4), the analytical model takes the form:

$$\begin{gathered} e_{d2}\left(\tau_d,\ q,\ N,\ n_d,\ K_p,\ \tau,\ L,\ C\right)= \\ =\frac{1}{2N}\sum_{k=0}^{\infty}\sum_{i=1}^{N}\left\{\left[1+\chi\left(\frac{\operatorname{floor}\left[u(k\tau_d)2^{n_d}\right]}{2^{n_d}},\ \frac{\operatorname{floor}\left[\mathrm{v}(i,\ k\tau_d,\ q)K_p\right]}{K_p},\ \tau\right)\right]\times\left[H(L_i,\ C)\right]\right\}, \end{gathered} \tag{3}$$

where $\tau = \{\tau_{on}, \tau_{off}, \tau_r, \tau_f\}$ – a set of parameters' values that determine the inertial properties of transistors ((τ_{on} – turn-on delay time, τ_{off} – turn-off delay time, τ_r – rise time, τ_f – fall time); $H(L_i, C)$ – transfer function of the multi-input filter; Li – inductance at the output of the i-th cell; C – filter capacity; $L = \{L_1, L_2, ..., L_N\}$ – a set of inductances in the LPF.

Finally, if it is required to evaluate the influence of the spread of turn-on and turn-off times of transistors (point 3), then this is achieved by another modification of the model: by introducing into the set of parameters that determine the inertial properties of transistors the required distribution law of the random variable and the dispersion σ, which, as a rule, can be selected from the data provided by the manufacturer. Further, for definiteness, we will proceed from the fact that the scatter of the parameters of the MPS elements obeys the normal law.

To take into account the influence of the spread in expression (3), the set of parameter values τ that determine the transistors' inertial properties should be represented as: $\tau = \{\tau_{on} + \sigma_{on}, \tau_{off} + \sigma_{off}, \tau_r + \sigma_r, \tau_f + \sigma_f\}$, where $\sigma_{on}, \sigma_{off}, \sigma_r, \sigma_f$ – the dispersions, respectively, of the turn-on and turn-off times, rise and fall times.

Confirmation of the analytical model adequacy

To confirm the reliability of the presented analytical model of the MPS it's necessary to estimate the coincidence of the characteristics provided by model with the results of simulation. Simulation can be performed in any of the circuit simulators (*LTSpice*, *MicroCap*, *Multisim*, *Keysight ADS*, etc.), while to describe transistors, it is advisable to use their models provided by manufacturing companies.

The simulation was carried out with the following initial data: the number of cells $N = 4$, the relative duration of transistor's switching interval $t_{on}(t_{off}) \leq 0.02T$, where T is the period of the reference sawtooth voltage, $q = 15$, $n_d = 10$ bits, $K_p = 10$ bits , the second-order output LPF implemented in accordance with the Bessel approximation, its cutoff frequency was three times the frequency of the testing harmonic voltage.

Fig. 4*a* shows the normalized spectral diagram of the voltage u_{sp} obtained as a sum of voltages at the outputs of the MPS cells, and in Fig. 4*b* – normalized spectral diagram of the voltage e_{d2} at the output of the MPS filter at 10 % deviation of the first cell inductance from the nominal value. In Fig. 4, the red line corresponds to the simulation results, the blue line – to the analytical model which takes into account the inertial parameters of the transistors and the digital conversion error, and the green curves – to the results of the analytical model with digital conversion and without inertial parameters account.

From comparison of the analytical and simulation results, shown in Fig. 4, it follows that both their behavior and coincidence measure are quite convincing confirmation of the proposed analytical model authenticity. Parasitic spectral components near the frequency of the testing voltage ($f/f_{\max} = 1$) are due to the inertia of transistors switching process. In simulation (Fig. 4), their level is around 60...50 dB, and in the case of an analytical model, 70...65 dB, respectively.

The error of the analytical model in the case of taking into account the transistors inertial parameters is 15–30 %. Without considering inertial parameters the error increases up to 45–60 %. Similar results, taking into account the transfer function of the LPF, are also typical for the diagrams in Fig. 4*b*. However, in Fig. 4*b*, it can be seen also an increase in the components that are multiples of the PWM clock frequency, by an average of 15–30 dB, caused by a deviation from the nominal value of one of the inductances. At the same time, the coincidence between the results of analytical model and simulation in this part of the spectrum is rather high.

Speaking about the advantages associated with the use of an analytical model, it should be noted that the time expenditure when using it turned out to be 200–300 times less than in the case of simulation modelling. This circumstance is especially important when it becomes necessary to carry out statistical modelling, for example, when studying the influence of the spread of parameters of transistors and passive components of circuits on signal distortion. It is obvious that the introduction of parameters' dispersion into the MPS simulation model, which determine the inertial properties of active elements and their properties in the turn-on state, is a rather complicated and sometimes impossible task as some companies enable no model editing.

Research results

The proposed analytical model was used to evaluate distortions influence that occur while amplifying the envelope voltage of a multi-frequency signal in the MPS, assuming that the RF power amplifier does not introduce distortions.

The goal of modeling was to determine how bit error rate affected by the following factors:

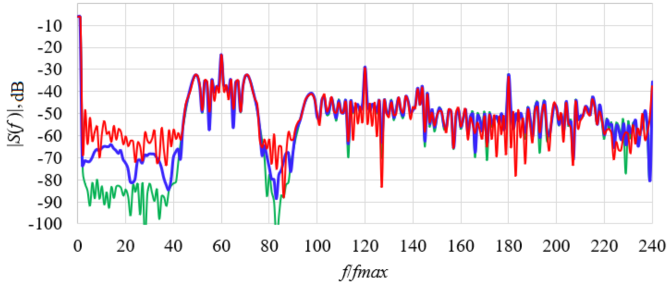
– parameters that determine the inertia of transistors (the turn-on and turn-off time, voltage rise and fall, included in the previously introduced vector τ);

– transistors' on-state voltage drop;

– statistical dispersion of the above transistors' parameters, as well as the ratings of some circuit passive elements;

– parameters of input signal and PWM reference voltage digital conversion.

a)



b)

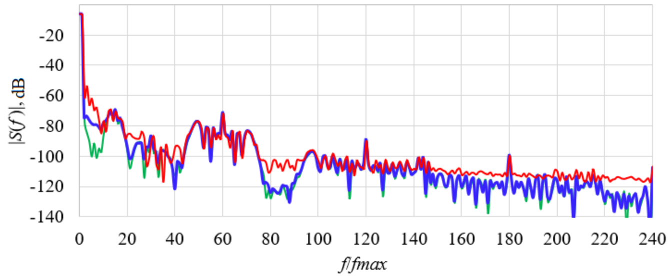


Fig. 4. Spectral diagrams of voltage u_{sp} (*a*), spectral diagrams of voltage e_{d2} (*b*)

The simulation was carried out for an OFDM signal with QAM-16. This choice was made intentionally, since it was found in [23] that QAM signals had stronger dependence of the bit error rate upon amplitude distortion than, for example, FSK signals. The results below correspond to the case of using a 4th order Bessel LPF with a bandwidth of five times the bandwidth occupied by the subcarriers of the test RF signal, which was conventionally taken as the frequency F_{max}, at $q = 15$, $n_d = 10$ bits, $K_p = 10$ bits. The filter type and its bandwidth correspond to the recommendations [2, 24].

The numerical experiment was carried out on the basis of statistical modeling, which included 1000 tests. For each test in the regions I – III, the averaged values of the corresponding spectral components were determined.

Estimation influence of transistors and MPS scheme elements parameters. Fig. 5*a* shows the dependences of the spectral components in region I (see Fig. 3) on the ratio τ/T. At the same time, in the region II, this dependence repeats the curve in Fig. 5*a*, for this reason, it is not shown. Fig. 5*b* shows a diagram of the dependence of the level of spectral components, multiples of the PWM clock frequency (region III), on the ratio τ/T. It should be noted that the study was carried out with a deviation of the parameters that determine the inertial properties of active elements within 10 % of the nominal value.

Fig. 5*a* shows that an increase in the vector τ from tenths of a percent to 10 % leads to an increase in the spectral components in the regions I and II by almost 50 dB. Moreover, a similar trend is observed with respect to components that are multiples of the PWM clock frequency. Besides, the spectral components in the III region can increase by almost 40 dB. The results obtained indicate that the use of a low-speed transistors can have a very negative impact on both the distortion of the RF signal and the level of out-of-band emission.

A study of transistors on-state voltage drop effect on spectrum distortions showed that when it changes by a factor of 50 in the range from 0.1 % to 5 % of the total voltage on the active element in the regions I and II, the spurious spectral components practically remain unchanged at the level of –105...–106 dB. For this reason, these dependencies are not shown in the paper. However, an increase in the on-state voltage drop

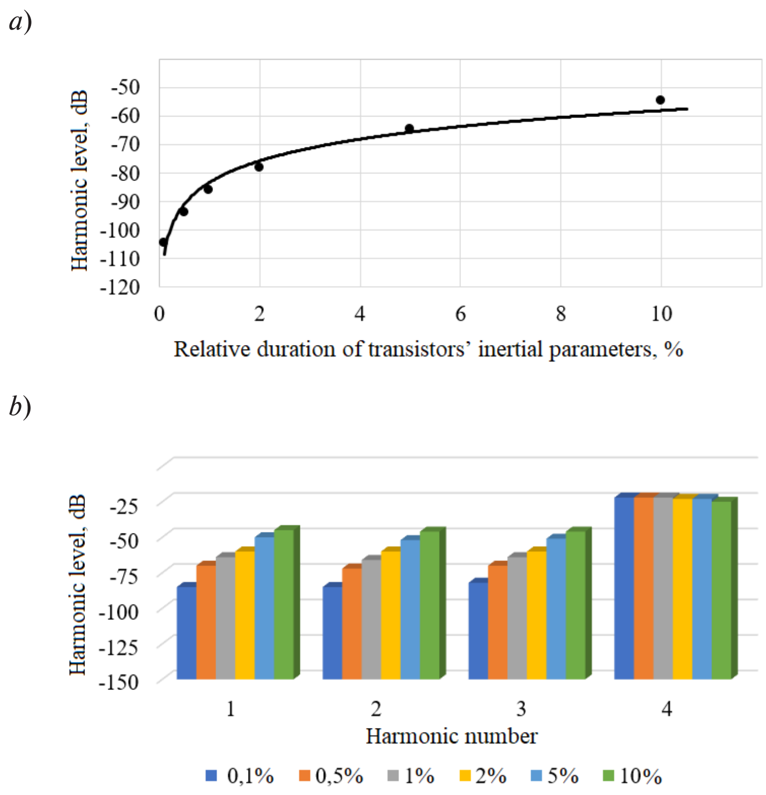


Fig. 5. The level of spectral components in the signal band (*a*), the level of spectral components that are multiples of the PWM clock frequency (*b*) for $\tau/T = 0.001; 0.005; 0.01; 0.02; 0.05; 0.1$

causes an increase in the components that are multiples of the PWM clock frequency, which is confirmed by the diagram shown in Fig. 6.

Figure 6 shows that with an increase in the normalized on-state voltage drop on transistors in the range from 0.1 % to 5 %, the first and second harmonics of the PWM clock frequency increase by almost 40 dB and can create certain problems in terms of out-of-band emissions. It should be noted that this change in the on-state voltage drop is not accompanied by an increase distortion in the signal band. This allows us to conclude that the on-state voltage drop does not affect a bit error rate when receiving a signal.

It was shown in [13] that the error in the phase setting between the output voltages of the MPS cells causes an increase in the spectral components that are multiples of the PWM clock frequency. However, it is important not only to determine the degree of influence of the error on these components, but also to find out whether it causes a distortion in the regions I and II. Figure 7 shows the results demonstrating the effect of the specified MPS parameter on the level of components that are multiples of the PWM clock frequency.

The magnitude of the phase's deviation of the cells output voltages is expressed as a percentage of the period of the PWM reference voltage. It should be noted that with a phase deviation reaching 10 %, the level of the components in the regions I and II increases by no more than 1–2 dB, remaining within the range of –90...–100 dB. Phase deviations have a more significant effect on components that are multiples of the clock frequency: for example, with an error of 10 %, the first harmonic of the clock frequency increases by almost 40 dB and can cause the problems mentioned above.

The effect of the inductances dispersion installed at the outputs of the MPS cells has a character similar to the effect of phase deviation. This is confirmed by Fig. 8, which shows the dependences of the spectral components level in the region III for a set of values of the normalized inductances dispersion from the

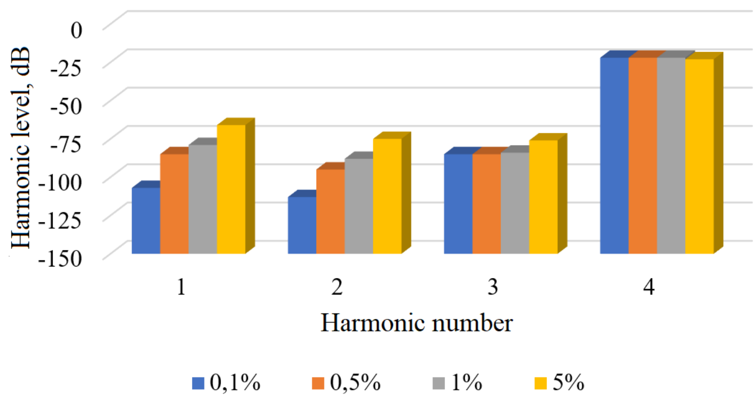


Fig. 6. Spectral components, multiples of the PWM clock frequency, depending on the magnitude of the on-state voltage drop

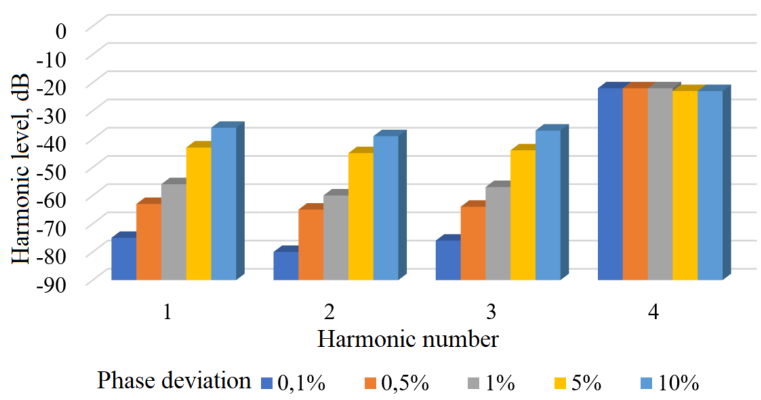


Fig. 7. The level of spectral components in the region III depending on the phases' deviation of the MPS cells' output voltages

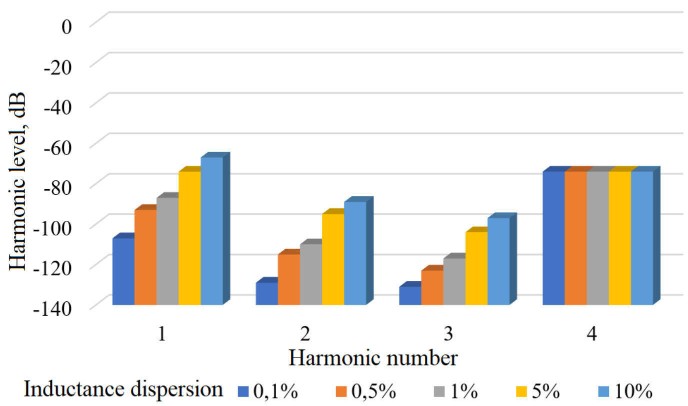


Fig. 8. The magnitudes of spectral components, multiples of the PWM clock frequency, depending on the dispersion of the inductances at the MPS cells' outputs

calculated values. In regions I and II, the spectral components level does not depend on the dispersion of inductances and is in the range of –95...–101 dB.

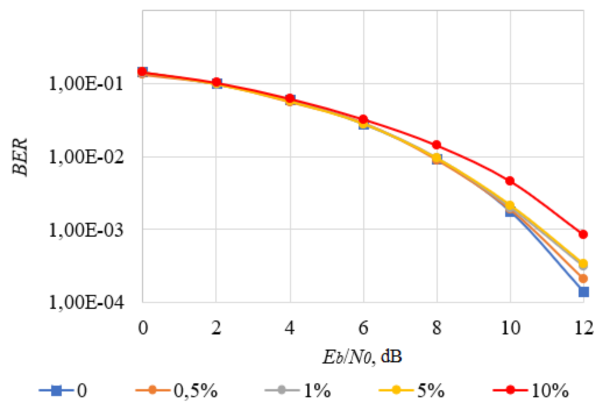
Fig. 8 shows that the level of spectral components that are multiples of the PWM clock frequency increases by 40 dB, which can also cause an increase in out-of-band emission.

Summarizing the obtained results, we can conclude that the most noticeable effect on the distortion of the envelope signal spectrum is caused by the insufficient speed of transistors. The transistors on-state voltage drop and the dispersion of inductances at the input of the LPF do not distort the spectrum in the band of the envelope signal, but mainly cause an increase in the multiples of the clock frequency.

Estimation bit error rate due to envelope voltage distortion. To assess how much the factors discussed above influence on the bit error rate, a numerical experiment was carried out using a communication channel model with additive Gaussian noise, while the number of tests was 10000. An OFDM signal based on 12 and 80 subcarriers with QAM-16 was used as a test signal. The numerical values of the MPS parameters used in the simulation are given in Section 5 of the paper.

Figure 9*a*, *b* shows the dependence of the bit error rate on the signal-to-noise ratio for an OFDM signal based on 12 and 80 subcarriers, respectively, calculated for different values of the parameters $\tau = \{\tau_{on} + \sigma_{on}, \tau_{off} + \sigma_{off}, \tau_r + \sigma_r, \tau_f + \sigma_f\}$, where $\sigma_{on} = 0.1\tau_{on}$, $\sigma_{off} = 0.1\tau_{off}$, $\sigma_r = 0.1\tau_r$, $\sigma_f = 0.1\tau_f$. In these figures, the zero value of the parameter along the abscissa axis corresponds to the idealized case, in which the influence of the MPS parameters is not taken into account. As the study showed, the energy loss due to the influence of other MPS parameters does not exceed 0.3 dB with a bit error rate of 10^{-3}.

a)



b)

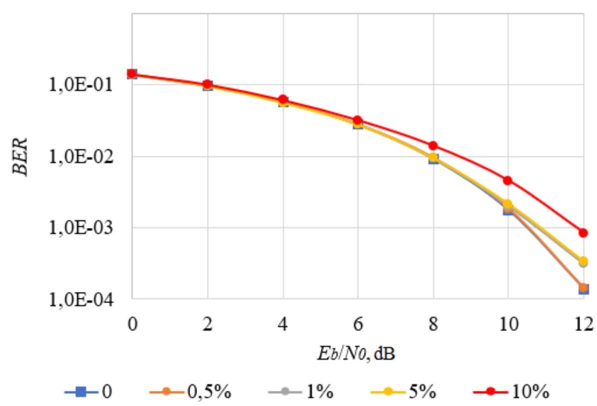


Fig. 9. BER as a function of signal-to-noise ratio for different τ/T

Analyzing the results presented in Fig. 9, the following conclusions can be made. The parameters that determine the inertial properties of active elements, as expected, affect the bit error rate. However, this is observed when the value of these parameters is in the region of 10 % of the PWM reference voltage period. In practice, this means the use of transistors with rather high switching times.

The influence of the dispersion of the MPS cells output voltages phases, the inductances at the input of the low-pass filter, the transistors' on-state voltage drop on the bit error rate is less expressed. The energy loss does not exceed tenths of a decibel.

Conclusion

Summarizing of the results presented above leads to the following conclusions.

1. The most significant influence on the distortion of the envelope signal, both in terms of increasing the level of bit error rate and in terms of spectrum degradation, is exerted by the inertia of transistors. For the QAM-16 signals considered as an example, this effect starts at $\tau/T \geq 0.005$ and, with a bit error rate of 10^{-3}, causes an energy loss of the order of 1.5 dB. Moreover, this pattern persists with an increase in the number of subcarriers in the OFDM signal from 12 to 80.

2. The transistors on-state voltage drop, the phase deviation of the output voltages of the MPS, and the dispersion of inductances at the outputs of the MPS cells do not have a pronounced effect on the bit error rate, regardless of the number of subcarriers (12 or 80).

3. It was found that the parameters listed in Section 2, under certain conditions, contributed to the appearance of spectral components that are multiples of the PWM clock frequency. Based on the allowable level of parasitic components equal to –80 dB, then the dispersion of inductance ratings should not exceed 1 %, and the phase deviation of the output voltages of the MPS cells should not exceed 0.1 %. Failure to follow these recommendations may result in an increase in the level of out-of-band emissions.

4. The proposed approach can be extended to arbitrary types of signals with a relatively high peak-to-average power ratio, which are amplified using the envelope tracking method.

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