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SPECTRUM TRANSFORMATION OF AN AMPLITUDE-MODULATED SIGNAL ON AN OHMIC NONLINEAR ELEMENT

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Introduction. In many physical processes, the spectrum of the modulated signal is transferred to the low-frequency region, which also manifests itself in active dielectrics in radio sound. In the general case, the analysis of the spectrum transformation process is a very difficult task related with solving a system of nonlinear differential equations. And in the accepted form, the principle of superposition is not applicable here, since the parameters of the output signal cannot be determined by algebraic summation of the signals received separately from each source. The spectrum of an input amplitude-modulated signal is nonlinearly related to the spectrum at the output. **Aim.** The conversion of the current spectrum under supplying an amplitude-modulated voltage to an active non-linear element with a non-linear current-voltage characteristic is considered. **Materials and methods.** In the analysis of the spectral transformation, a power approximation of the current-voltage characteristic in the form of a polynomial of the third degree with trigonometric functions is used. In the examples, spectrum transformations for a mono signal, amplitude-modulated signal, and beats are considered. Application of amplitude modulation methods is essential for transferring the spectrum of the signal to the low frequency region. **Results.** A graphical representation of the dependence of the current function on time for an AM signal and beats, as well as their spectral representation, is given. **Conclusion.** The paper analyzes the transformation of the signal spectrum for the current when applying any, but amplitude-modulated voltage on the ohmic nonlinear element. The carrier signal is represented as a harmonic trigonometric function of the cosine of the current time. However, signal spectrum conversion has not related with detection.

Keywords: nonlinear element, current-voltage characteristic, amplitude modulation, beats.

Introduction

In many physical processes, the spectrum of the modulated signal is transferred to the low-frequency region, for example, in the occurrence of radio sound in active dielectrics [1] or the appearance of an acoustic signal at the beats frequency during the interaction of signals from two ultrasonic sources [2]. In the general case, the analysis of the spectrum transformation process is a very difficult task related to solving a system of nonlinear differential equations. And in this case, the principle of superposition is not applicable. Nevertheless, research and analysis can be carried out using relatively simple methods if the form of the current-voltage characteristic (CVC) for a nonlinear element (NE) in the dynamic mode is the same as for a constant voltage (or in static mode). Such a NE is called a resistive inertialess element [3, 4]. Physically inertialess NE means the appearance of a response in the form of a function of time from the current $i(t)$ after the input action as a function of time from the voltage $u(t)$. Formally, there are practically not inertialless NE. At the same time, many modern circuit elements are perfect in their frequency parameters and can be idealized from the point of view of their inertialess. Such elements are called not only resistive, but also active or ohmic [5].

In order to effectively transmit signals in any environ, it is necessary to transfer the spectrum of these signals from the low-frequency region to the region of sufficiently high frequencies. This procedure is called modulation in communication technology. The frequency ω for the physical information carrier is selected taking into account the peculiarities of the propagation of oscillations in communication lines or in the environ of radio communication. But in any case, the frequency ω is much higher than the highest frequency Ω of the primary signal, which performs modulation [5, 6].

Under these conditions, the parameters of the modulated oscillation change slowly compared to the rate of change of the carrier oscillation. In one period of the modulating signal $T_F = 1/F = 2\pi/\Omega$ usually contain hundreds, thousands and more periods of high-frequency oscillations. Consequently, during several periods of the last $T_f = 1/f = 2\pi/\omega$, only slight changes in the parameters of the modulating signal occurs [7, 8].

1. The concept of current-voltage characteristics (CVC)

CVC – a special case of the transfer characteristics that determine the dependence (function) of the output quantity on the input for a given specific device or circuit. CVC is a graph of the current through a two-terminal circuit versus the voltage at this two-terminal circuit. CVC characteristic describes the behavior of a two-terminal circuit in static mode. Most often, the analysis of nonlinear elements by CVC degree of nonlinearity, which is determined by the coefficient of nonlinearity $K = \frac{UdI}{IdU}$. For linear elements, CVC is a straight line and is not of particular interest [7, 8].

While analyzing the spectral transformation under the influence of harmonic voltage, for example, a power-law approximation in the form of a polynomial with trigonometric functions is used:

$$i(t) = b_0 + b_1 U_m \cos \omega t + b_2 U_m^2 \cos^2 \omega t + b_3 U_m^3 \cos^3 \omega t, \quad (1)$$

where we limit ourselves to a polynomial of the third degree. Here b_i – dimensional parameters; b_0 – constant component is not of interest in the work.

Example 1.

1. If $t = 0$ c, $R = 1$ Ohm, then based on Ohm's law from (1) we obtain:

$$I = U, \quad (2)$$

where CVC (and below in the example) is represented in **dimensionless form**.

2. If $b_1 = 1, b_2 = 0, b_3 = 1$ of (1) we get:

$$I_1 = U + U^3. \quad (3)$$

3. If $b_1 = 1,\ b_2 = 0{,}5,\ b_3 = 1$ of (1) we get:

$$I_2 = U + 0{,}5U^2 + U^3. \quad (4)$$

4. If $b_1 = 1,\ b_2 = 1,\ b_3 = 1$ of (1) we get:

$$I_3 = U + U^2 + U^3. \quad (5)$$

5. If $b_1 = 1,\ b_2 = 2,\ b_3 = 1$ of (1) we get:

$$I_4 = U + 2U^2 + U^3. \quad (6)$$

CVC for **example 1** in dimensionless form are presented in Fig. 1.

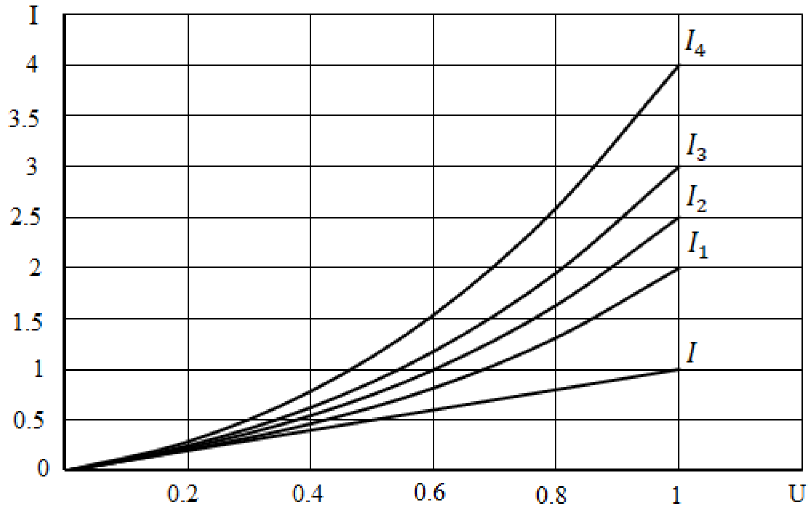

Fig. 1. Dimensionless form of CVC for example 1

2. Spectrum transformation for a mono signal

Consider the analysis of an example of a current spectrum under supplying a harmonic voltage. When the element is linear, then receive harmonic current (one component). When the element is nonlinear, then receive a lot of components [6].

For the spectrum concept, it is important to find the amplitude spectral components and initial phases. The frequencies of all components will be multiples of the fundamental frequency or the frequency of exposure [7–12].

The best choice of approximation method depends on the type of nonlinear characteristic, as well as on the mode of operation of the nonlinear element. One of the most common methods is power polynomial approximation [13–15].

In the analysis of the spectral transformation under the influence of harmonic voltage, for example, a power approximation in the form of a polynomial with trigonometric functions is used:

$$i(t) = b_0 + b_1 U_m \cos \omega t + b_2 U_m^2 \cos^2 \omega t + b_3 U_m^3 \cos^3 \omega t + \cdots + b_n U_m^n \cos^n \omega t, \quad (7)$$

where U_m [V] – voltage amplitude; b_0 [A] – constant current component; b_1 [Ohm^{-1}·V^{-1}], b_2 [Ohm^{-2}·V^{-2}]… – dimensional coefficients.

When using the cosines of all the initial phase is zero. In this paper, we mainly limit ourselves to the polynomial of the third degree (1).

Example 2.

Given: $b_0 = 0,\ b_1 = 1,\ b_2 = 0,\ b_3 = 1,\ U_m = 1$. Determine the current.

Solution. If $b_2 = 0$, then applying the degree reduction formula

$\cos^3 \omega t = \frac{\cos 3\omega t + 3\cos \omega t}{4}$.

From (1) we get the expression for current:

$$i(t) = \left(\frac{3 b_3 U_m^3}{4} + b_1 U_m\right) \cos \omega t + \frac{b_3 U_m^3}{4} \cos 3\omega t. \quad (8)$$

The result is shown in Fig. 2.

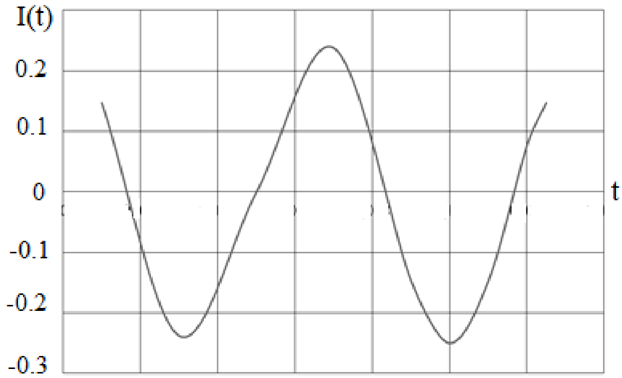

Fig. 2. Current function versus time for example 2

3. Spectrum transformation for amplitude-modulated signal

Under AM, the spectrum of the modulating signal is transmitted to the region of the carrier frequency, forming the upper and lower side components of the spectrum. Since such a transformation creates new frequencies, the modulation procedure is a nonlinear transformation. But since the AM spectrum of the modulating signal does not change, but is transmitted only to the high-frequency region, AM is considered a type of linear modulation. In many cases, the spectrum of the AM signal is relatively simple and can be determined from the spectrum of the modulating signal, which is noticeably simpler than its direct calculation. The basic relationships required for this can be relatively easily obtained using the example of the AM signal when the AM signal is performed by a harmonic signal [9–13].

Carrier frequency, frequency of harmonic oscillations subjected to modulation by signals for transmitting information. Low-frequency oscillations are sometimes called carrier oscillations. The oscillations with the LF themselves do not contain information, they only “carry” it. The spectrum of modulated oscillations contains, in addition to low frequencies, side frequencies, which contain the transmitted information [4].

Every modulated oscillation is non-sinusoidal and has a complex spectrum. Consider an amplitude-modulated signal in the simplest case where the modulating function represents a sinusoidal character. The voltage acting on the NE:

$$u(t) = U\ \cos\omega_0\, t + \frac{m}{2} U\ (\cos(\omega_0 + \Omega) + \cos(\omega_0 - \Omega)\, t), \tag{9}$$

where U – is the amplitude; m – is the modulation depth; ω_0 – is the carrier frequency; Ω – is the modulation frequency.

We apply by analogy the substitution $u(t)$ in (1). The analysis of the validity of this formal substitution is not discussed in the work, but in the field of LF is not in doubt. So, we get:

$$i(t) = b_1\left(U\cos\omega_0 t + \frac{m}{2}U(\cos(\omega_0+\Omega)t + \cos(\omega_0-\Omega)t)\right) +$$
$$+ b_2\left(\mathrm{U}\cos\omega_0 t + \frac{m}{2}\mathrm{U}(\cos(\omega_0+\Omega)t + \cos(\omega_0-\Omega)t)\right)^2 +$$
$$+ b_3\left(\mathrm{U}\cos\omega_0 t + \frac{m}{2}\mathrm{U}(\cos(\omega_0+\Omega)t + \cos(\omega_0-\Omega)t)\right)^3. \tag{10}$$

Next, we use the following formulas to reduce the degrees:

$$\cos^2\omega t = \frac{\cos 2\omega t + 1}{2}; \tag{11}$$

$$\cos^3\omega t = \frac{\cos 3\omega t + 3\cos\omega t}{4}. \tag{12}$$

For current $i(t)$ because of substitution, we obtain:

$$i(t) = \frac{1}{2}b_2U^2 + \frac{m^2}{4}b_2U^2 + mb_2U^2\cos\Omega t + \frac{m^2}{4}b_2U^2\cos 2\Omega t +$$
$$+\left(\frac{m}{2}b_1U + \frac{9m}{8}b_3U^3 + \frac{9m^3}{32}b_3U^3\right)\cos(\omega_0-\Omega)t + \left(b_1U + \frac{3}{4}b_3U^3 + \frac{9m^2}{8}b_3U^3\right)\cos\omega_0 t +$$
$$+\left(\frac{m}{2}b_1U + \frac{9m}{8}b_3U^3 + \frac{9m^3}{32}b_3U^3\right)\cos(\omega_0+\Omega)t + \frac{9m^2}{16}b_3U^3\cos(\omega_0-2\Omega)t \ldots \tag{13}$$

Here and below, the low-frequency components of the spectrum are of interest.

Example 3. Given: $m = 1,\ b_0 = 0,\ b_1 = 1,\ b_2 = 1,\ b_3 = 1,\ U = 1$. Determine the low frequency current.

Solution. From (13) we get the current LF:

$$\text{LF}: i(t) = \frac{1}{2}b_2U^2 + \frac{m^2}{4}b_2U^2 + mb_2U^2\cos\Omega t + \frac{m^2}{4}b_2U^2\cos 2\Omega t. \tag{14}$$

There is a constant component and there are two harmonics. For Fig. 3 and 4 the results are presented as reamers of the signal and its spectrum.

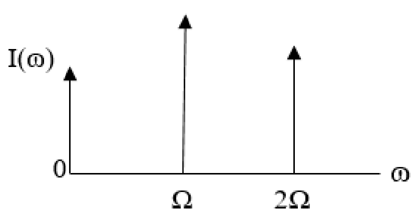

Fig. 3. The spectrum of the signal with amplitude modulation for example 3

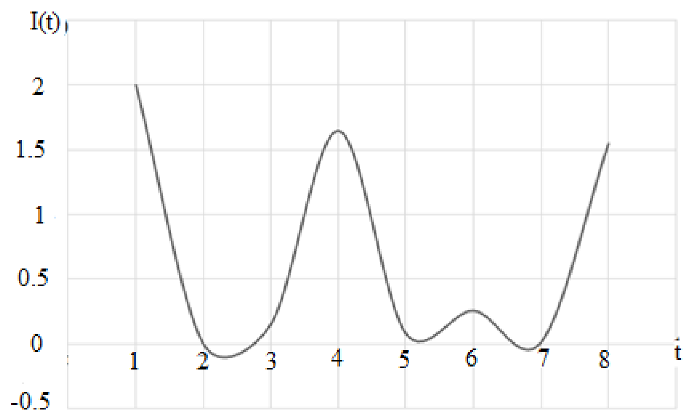

Fig. 4. The dependence of the function of current on time for example 3

Example 4. In the dimensionless form, it is given: $m = 1, b_0 = 0, b_1 = 1, b_2 = 0,\ b_3 = 1, U = 1$. Determine the low frequency current.

Solution. If $b_2 = 0$, then (14) results in the absence of a low-frequency current and a constant component.

4. Beat Spectrum transformation

Beats occur due to the fact that one of the two signals is linear in time lags the other in phase, and at those moments when the oscillations coincide in phase, the total signal is the maximum, and at those moments when the two signals are not in phase, they mutually suppress each other. These moments periodically replace each other as the lag increases [4].

If at the same time two tuning-forks with slightly different frequencies are slightly excited, the resulting sound periodically oscillates and decays. These modulations are called beats; their frequency is equal to the difference in frequency of the initial tones. Beats are obtained when electrical signals from the outputs of two generators are mixed and fed to the speaker. On the other hand, these same signals can be simultaneously applied to two different dynamics and also hear beats [5].

Beats relate to amplitude modulation, but without a carrier frequency. Consider the addition of two high-frequency oscillations:

$$u = u_1 + u_2 = U_1 \cos(\omega - \Omega)t + U_2 \cos(\omega + \Omega)t, \quad (15)$$

where the difference frequency $\Delta\omega = 2\Omega$.

To analyze the spectral transformation of beats we write an approximating power polynomial with trigonometric cosine functions in the form:

$$i(t) = b_1(U_1 \cos(\omega_0 - \Omega)t + U_1 \cos(\omega_0 + \Omega)\, t) +$$
$$+ b_2(U_1 \cos(\omega_0 - \Omega)t + U_1 \cos(\omega_0 + \Omega)\, t)^2 +$$
$$+ b_3(U_1 \cos(\omega_0 - \Omega)t + U_1 \cos(\omega_0 + \Omega)\, t)^3. \quad (16)$$

We use the formulas for lowering the degrees (11) and (12) below to transform. We obtain

$$i(t) = \frac{1}{2}b_2U_1^2 + \frac{1}{2}b_2U_2^2 + b_2U_1U_2\cos 2\Omega t + \left(b_1U_1 + \frac{3}{4}b_3U_1^3 + \frac{3}{2}b_3U_1U_2\right)\cos(\omega - \Omega)t +$$
$$+ \left(b_1U_2 + \frac{3}{4}b_3U_2^3 + \frac{3}{2}b_3U_1U_2\right)\cos(\omega + \Omega)t + b_2U_1U_2\cos 2\omega t +$$
$$+ \frac{1}{2}b_2U_1^2\cos 2(\omega - \Omega)t + \frac{1}{2}b_2U_2^2\cos 2(\omega + \Omega)t + \cdots \quad (17)$$

In Fig. 5 and 6 shows the results in the form of a sweep of the signal and its spectrum.

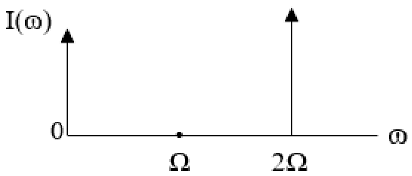

Fig. 5. Low-frequency spectrum for beats: constant component and frequency 2Ω

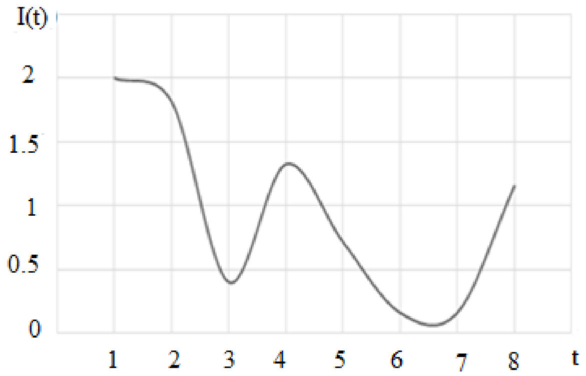

Fig. 6. The dependence of the LF current on time for beats

If we substitute $b_2 = 0$, in polynomial (17), then we obtain for the current:

$$i(t) = \left(b_1U_2 + \frac{3}{4}b_3U_2^3 + \frac{3}{2}b_3U_1U_2\right)\cos(\omega - \Omega)t +$$
$$+ \left(b_1U_2 + \frac{3}{4}b_3U_2^3 + \frac{3}{2}b_3U_1U_2\right)\cos(\omega + \Omega)t + \frac{3}{4}b_3U_1U_2\cos(\omega - 3\Omega)t +$$
$$+ \frac{3}{4}b_3U_1U_2\cos(\omega + 3\Omega)t + \frac{3}{4}b_3U_1U_2\cos(3\omega - \Omega)t + \frac{3}{4}b_3U_1U_2\cos(3\omega + \Omega)t +$$
$$+ \frac{1}{4}b_3U_1^3\cos 3(\omega - \Omega)t + \frac{1}{4}b_3U_1^3\cos 3(\omega + \Omega)t. \quad (18)$$

There are no low frequencies and no constant component in this polynomial.

Conclusion

The transformation for the current spectrum under supplying a modulated voltage to an ohmic nonlinear element is considered. Transformation for any type of amplitude modulation to the low-frequency region is observed when there is a quadratic nonlinearity of the CVC. Similar transformations can be observed in active dielectrics, for example, in piezoceramics. In the presented examples, the transformation process has nothing to do with signal detection.

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ПРЕОБРАЗОВАНИЕ СПЕКТРА АМПЛИТУДНО-МОДУЛИРОВАННОГО СИГНАЛА НА ОМИЧЕСКОМ НЕЛИНЕЙНОМ ЭЛЕМЕНТЕ

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Введение. Во многих физических процессах наблюдается перенос спектра модулированного сигнала в низкочастотную область, что проявляется и в активных диэлектриках при радиозвуке. В общем случае анализ процесса преобразования спектра является очень сложной задачей, связанной с решением системы нелинейных дифференциальных уравнений. И в принятой форме принцип суперпозиции здесь не применим, поскольку параметры выходного сигнала не могут быть определены алгебраическим суммированием сигналов, получаемых раздельно от каждого источника. Спектр входного амплитудно-модулированного сигнала нелинейным образом связан со спектром на выходе. **Цель исследования.** Рассматривается преобразование спектра тока при подаче амплитудно-модулированного напряжения на активный нелинейный элемент с нелинейной вольтамперной характеристикой. **Материалы и методы.** В анализе спектрального преобразования применяется степенная аппроксимация вольтамперной характеристики в виде полинома третьей степени с тригонометрическими функциями. В примерах рассматриваются преобразования спектра для моносигнала, амплитудно-модулированного сигнала и биений. Применение амплитудных методов модуляции необходимо для переноса спектра сигнала в область низких частот. **Результаты.** Приводится графическое представление зависимости функции тока от времени для амплитудно-модулированного сигнала и биений, а также их спектрального представления. **Заключение.** В работе анализируется преобразование спектра сигнала для тока при подаче амплитудно-модулированного напряжения на омическом нелинейном элементе. Несущий сигнал представлен в виде гармонических тригонометрических функций косинуса текущего времени. Однако преобразование спектра сигнала никак не связано с детектированием.

Ключевые слова: нелинейный элемент, вольтамперная характеристика, амплитудная модуляция, биения.

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