Conclusion

The suggested algorithm of determination of resonance frequency changing bounds and Q factor of tuned circuit allows us to define circuit parameters at changes of heated object temperature at specified values of gap size between the inductor and the object, number of windings and inductor current, nominal frequency.

On the basis of the algorithm dependences of range boundaries of proper frequency change and Q factor of a circuit on design and electric values of the system «inductor – heated object» were obtained. It is stated that with a rise of gap size between the inductor and heated element and increase of number of windings subject to constancy of nominal resonance frequency, range of frequency changing decreases to zero. Peak of resonance frequency changing is obtained at zero gap size between the inductor and heated object. Significant increase of Q factor of tuned circuit with a rise of gap size and nominal resonance frequency is stated.

REFERENCES

1. Sluhotskiy A.E. Induction heating installations. – Leningrad: Energoizdat, 1981. – 325 p.
2. Osipov A.V. Systems of high-frequency induction heating of blocks before plastic deformation. Abstract of a thesis ... of a and. of tech. science. – Tomsk, 2004. – 18 p.
3. Vladimirov S.N., Zeman S.K., Osipov A.V., Tolstov V.P. Peculiarities of ferromagnetic steels induction heating at different modes of operation of frequency transformer // Proceedings of Higher Schools. Electromechanics. – 2004. – № 1. – P. 50–54.
4. Romash E.M., Drabovich Yu.I., Yurchenko N.N., Shevchenko P.N. High-frequency transistor converters. – Moscow: Radio and communication, 1988. – 288 p.

Arrived on 04.09.2006

UDC 621.382.323

NONLINEAR DISTORTION ANALYSIS OF PASSIVE FET ATTENUATORS

V.I. Tuev

Tomsk State University of Control Systems and Radio Electronics
E-mail: tvi@tv2.tomsk.ru

The FET passive attenuator nonlinear transfer function design method is suggested. Method permits to compute regulation curve and nonlinear distortion passive attenuator on JFETs, MOSFETs and GaAs MESFETs. Results of researching attenuators with parallel, series and combined connection of varied elements are presented.

Passive electrically controlled attenuators where field-effect transistors (FET) are used as two-terminal networks with variable characteristics, are applied in systems of automatically gain control of receiving and transmitting channels of communication and television equipment, in communication systems, in measuring equipment, in audio reproduction equipment as volume regulators etc. [1, 2]. The problem of calculation of nonlinear distortions in these devices is not finally solved. Well-known results have a particular character [2, 3] conditioned by used approximation of output volt-ampere characteristics of a specific type transistor, have qualitative and quantitative discrepancies between experimental data.

The purpose of the paper is to derive a mathematical expressions for design of nonlinear distortions in FET passive attenuators. Formula derivation was made in the course of nonlinear current method, applied for design of nonlinear transfer functions of Volterra type circuits [4].

Typical circuits of mostly used attenuators are presented in fig. 1 [2].

Simulation of FET properties as controlled two-terminal network is based on application of analytical description of nonlinear relation of drain current I_D from voltages on a gate U_1 and on a drain U_2 relative to internal source, connected with external terminal through parasitic resistance of uncontrolled part of a channel r_s:

$$I_C = \frac{I_0}{1-\left(\frac{U_2}{U_{ДОП}}\right)^n}\left(1-e^{-\frac{DU_2}{U_1-U_0'}}+FU_2\right)\times$$
$$\times\left(1+Qe^{-\sqrt{RU_2^{\psi_1}+T(|U_1|+V)^{\psi_2}}}\right), \qquad (1)$$

where

$$I_0 = A(U_1-U_0)^B\frac{1}{1+\left(\frac{U_1U_2}{P}\right)^K}, \qquad (2)$$

A, B, D, F, K, P, Q, R, T, ψ_1, ψ_2, n are the coefficients of approximation, U_0 is the threshold voltage (cutoff voltage), U_{MAX} is the maximum drain voltage, V is the built-in potential. A is a coefficient of proportionality, B is a coefficient characterizing the degree of nonlinearity dependence of I_D on U_1 in a flat area of drain volt-ampere characteristics. Coefficients P and K show the influence of carriers-drift velocity saturation in transistor channel. This effect appears significantly in power transistors, for low-power ones the third factor in (2) is equal 1.

The second factor in (1) characterizes output volt-ampere characteristics, summand describes the behavior of in a flat area and represents effects of channel shortening and electrostatic feedback between the drain and the channel in MOSFET. For JFETs and GaAs MESFETs F=0.

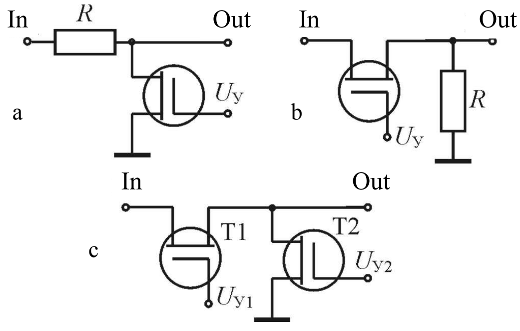

Fig. 1. *Typical circuits of passive attenuators in FET with parallel (a), series (b) and combined (c) connection of varied elements*

Coefficients Q, R, T, ψ_1, ψ_2 describes the influence of carriers-drift velocity saturation in average and high power GaAs MESFETs. For low-power GaAs MESFETs and Si MESFETs the third factor in (1) which contains these coefficients may be neglected.

Coefficient n represents I_C rise owing to carriers avalanche multiplication at drain region breakdown.

Numerical values of coefficients of approximation and value r_s for MOSFETs and GaAs MESFETs are presented in [5, 6] for some types of JFETs are shown in table 1.

The expressions (1, 2) with an error not more than 20 % describe the volt-ampere characteristics family at voltages on transistor gate from U_0 to 0 (JFET and GaAs MESFETs), from U_0 to the value conforming to peak drain current (MOSFETs) and in the drain voltages range from V to U_{MAX} for all types of FETs.

Table 1. *Coefficients of approximation and value $r_и$ for JFETs*

FET type	A	B	D	$r_и$, Om	U_0, V
KP103	0,76	1,95	1,10	20	1,25
KP303	1,53	1,57	0,90	12	–2,50
KP312	1,90	1,40	2,53	20	–4,75

The design of FET drain current alternating components according to nonlinear current method is performed in the form

$$i = \sum_{n=1}^{N} i_n, \qquad (3)$$

where N is the highest degree of allowed nonlinearity, i_n is n-order nonlinear current.

On the basis of a generalized formulas for design of nonlinear equivalent current sources of multioutlet active elements [7], the first three degrees current components (N=3), being of maximal practical interest [2–4], may be presented in the form

$$i_1 = \sum_{k=1}^{2} g_k^{(1)} u_k^{(1)}, \qquad (4)$$

$$i_2 = \sum_{k=1}^{3} i_{2_k}, \qquad (5)$$

$$i_{2_1} = g_1^{(2)} [u_1^{(1)}]^2, \; i_{2_2} = g_2^{(2)} [u_2^{(1)}]^2, \; i_{2_3} = g_{1,2}^{(1+1)} u_1^{(1)} u_2^{(1)}, \qquad (6)$$

$$i_3 = \sum_{k=1}^{8} i_{3_k}, \qquad (7)$$

$$i_{3_1} = g_1^{(3)}[u_1^{(1)}]^3, \; i_{3_2} = g_2^{(3)}[u_2^{(1)}]^3, \; i_{3_3} = g_{1,2}^{(2+1)}[u_1^{(1)}]^2 u_2^{(1)},$$
$$i_{3_4} = g_{1,2}^{(1+2)}[u_2^{(1)}]^2 u_1^{(1)}, \; i_{3_5} = 2g_1^{(2)} u_1^{(1)} u_1^{(2)}, \; i_{3_6} = g_2^{(2)} u_2^{(1)} u_2^{(2)},$$
$$i_{3_7} = 2g_{1,2}^{(1+1)} u_1^{(1)} u_2^{(2)}, \; i_{3_8} = 2g_{1,2}^{(1+1)} u_1^{(2)} u_2^{(1)}, \qquad (8)$$

where $g^{(.)}$ are particular and mixed conductivities, determined from representation (1) by Taylor multiple series in the neighborhood of working point, determined by bias voltages U_{10}, U_{20}:

$$g_{1,2}^{(m_1+m_2)} = \frac{1}{m_1! m_2!} \frac{\partial^{m_1+m_2} I_C(U_{10}, U_{20})}{\partial U_1^{m_1} \partial U_2^{m_2}}. \qquad (9)$$

The equivalent circuit of attenuator with parallel MESFET correct for alternating current is presented in fig. 2.

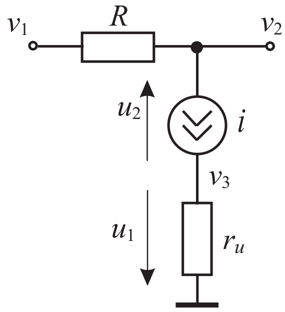

Fig. 2. *The equivalent circuit of attenuator with parallel connection FET: u_1 is voltage on a gate, u_2 is voltage on a drain relative to inner source*

The following ratios are right for nodal potentials in the circuit, fig. 2:

$$\begin{cases} v_2^{(n)} = v_1^{(n)} - Ri_n \\ v_3^{(n)} = r_u i_n \end{cases}. \qquad (10)$$

Here and then n = 1,...,N.

According to nonlinear current method the calculation of first degree nonlinear transfer functions, i.e. the attenuator regulation curve, is carried out at i=i_1 in (3). The numerical calculations show that at low drain voltages U_{20} (in a sharp area of output volt-ampere characteristics) the inequality $g_1^{(1)} << g_2^{(1)}$ is carried out, thus, the expression (4) may be simplified:

$$i_1 \approx g_2^{(1)} u_2^{(1)}. \qquad (11)$$

Solving the system of equations (10) in view of equation (11), we get normalized to the level of input signal nodal potentials and voltages

$$v_3^{(1)} = \frac{g_2^{(1)} r_u}{1 + g_2^{(1)}(r_u + R)}, \qquad (12)$$

$$v_2^{(1)} = \frac{1 + g_2^{(1)} r_u}{1 + g_2^{(1)}(r_u + R)}, \quad (13)$$

$$u_1^{(1)} = -v_3^{(1)} = \frac{-g_2^{(1)} r_u}{1 + g_2^{(1)}(r_u + R)}, \quad (14)$$

$$u_2^{(1)} = v_2^{(1)} - v_3^{(1)} = \frac{1}{1 + g_2^{(1)}(r_u + R)}. \quad (15)$$

The expression for calculation of the first order H_1 nonlinear transfer functions is given by the following form

$$H_1 = v_2^{(1)} = \frac{1 + g_2^{(1)} r_u}{1 + g_2^{(1)}(r_u + R)}. \quad (16)$$

The calculation of higher orders H_n nonlinear transfer functions is carried out according to similar ratios (10–15), obtained at $i=i_n$ and $v_1=0$:

$$v_3^{(n)} = i_n \frac{1 - \left(\frac{R}{(1+g_2^{(1)} r_u)(1+g_2^{(1)} R)}\right)\left(\frac{1}{R} + g_2^{(1)}\right)}{g_2^{(1)}}, \quad (17)$$

$$v_2^{(n)} = H_n = \frac{-i_n R}{(1 + g_2^{(1)} r_u)(1 + g_2^{(1)} R)}. \quad (18)$$

Let us calculate currents and determining partial and mixed derivatives according to (9) at control voltage variation $U_y = U_{10}$ in the range from U_0 to 0 and at fixed value U_{20}=0,6 V [8] replacing them into (5–8). The numerical values of current components for MOSFET KP305 [5] are presented in fig. 3. Nonlinearity of output conductivity $g_2^{(2)}$ makes a main contribution to nonlinear second order current. The third order nonlinear current is determined by the following components, presented in the order of their significance: by i_{3_8} component, generated owing to nonlinear-parametric interaction of linear drain voltage and second order gate voltage at second order mixed conductivity $g_{1,2}^{(1+1)}$; by i_{3_6} component, obtained by means of first and second orders voltages interaction at drain quadratic nonlinearity $g_2^{(2)}$; by i_{3_2} component, being the result of output cube nonlinearity conductivity $g_2^{(3)}$ influence.

The expressions for calculations of nonlinear transfer functions attenuators as with parallel so with series and combined connection FETs (fig. 1, *b*, *c*), founded as a result of the similar calculations, are presented in table 2.

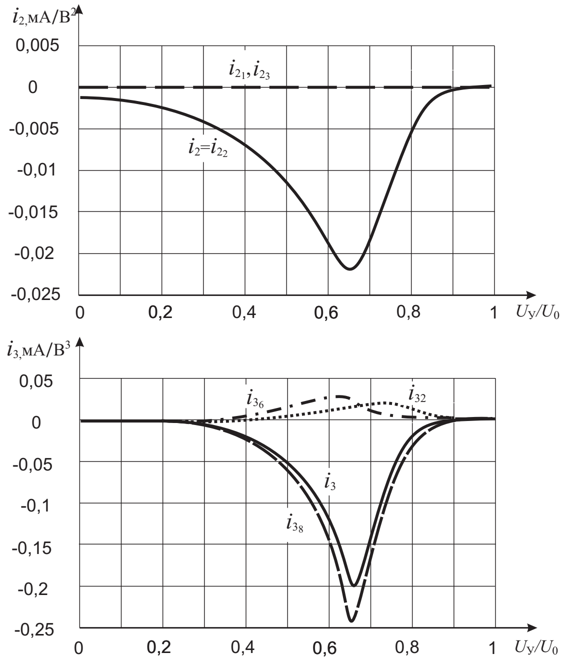

Fig. 3. *The components of nonlinear currents of the second and the third orders in the circuit of attenuator with parallel connection of MOSFET KP305 type*

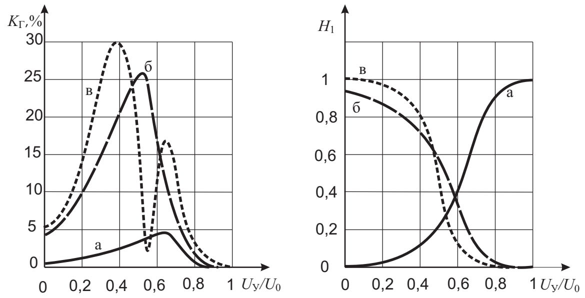

Fig. 4. *Regulation curves and harmonic factor K_H of attenuators with parallel at value R=24 kOm (a), series (R=10 kOm) (b) and combined (c) connection of varied elements*

The regulation curve and harmonic factor K_H in the transfer regulation range attenuators with parallel, series and combined connection of varied elements are presented in fig. 4. Calculated value of the harmonic factor is determined by the formulas

$$K_Г = \sqrt{K_{Г2}^2 + K_{Г3}^2}, \quad K_{Г2} = \frac{H_2 U_{вх}}{2H_1}, \quad K_{Г3} = \frac{H_3 (U_{вх})^2}{4H_1} \quad [2]$$

Table 2. *The expressions for calculations of nonlinear transfer functions attenuators with parallel, series and combined connection of controlled elements*

Function	Fig. 1, a	Fig. 1, b	Fig. 1, c
H_1	$\frac{1+g_2^{(1)} r_u}{1+g_2^{(1)}(r_u+R)}$	$\frac{g_2^{(1)} R}{1+g_2^{(1)}(r_u+R)}$	$\frac{1+[g_2^{(1)}]_{T2} r_u}{1+\frac{[g_2^{(1)}]_{T2}}{[g_2^{(1)}]_{T1}} + 2[g_2^{(1)}]_{T2} r_u}$
H_n	$\frac{-i_n R}{(1+g_2^{(1)} r_u)(1+g_2^{(1)} R)}$	$\frac{i_n R}{1+g_2^{(1)}(r_u+R)}$	$\frac{[i_n]_{T1} - [i_n]_{T2} \frac{1+[g_2^{(1)}]_{T1} r_u}{1+[g_2^{(1)}]_{T2} r_u}}{[g_2^{(1)}]_{T1} \frac{1+2[g_2^{(1)}]_{T2} r_u}{1+[g_2^{(1)}]_{T2} r_u} + \frac{[g_2^{(1)}]_{T2}}{1+[g_2^{(1)}]_{T2} r_u}}$

with root-mean-square value of input signal $U_{вх}$=100 mV. The calculation of parameters of attenuator with combined connection FETs is carried out at the following ratio of control voltages on the gates: $U_{y1}=U_y$; $U_{y2}=U_0-U_{y1}$.

To confirm the reliability of obtained theoretical results the experimental and calculated characteristics of attenuator with parallel MOSFET connection are presented in fig. 5.

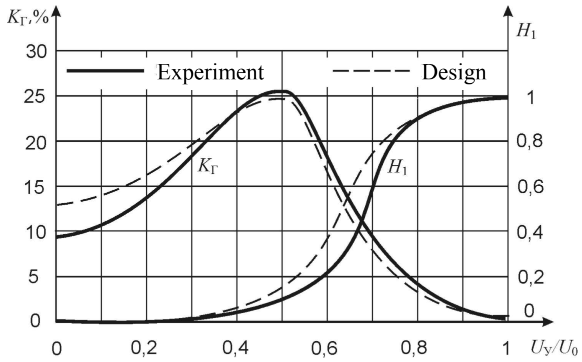

Fig. 5. *Regulation curves and harmonic factor of attenuator with parallel MOSFET connection KP305 type in the conditions of constant output voltage u_{out}=100 mV at frequency 1000 Hz*

In the range of control voltages from 0,3 to 1 variation of attenuator transmission coefficient is performed in the range from 0,01 to 1, i.e. on 40 dB. Discrepancy of calculation and experimental data in this range is not more than 20 %. In the area of control voltages from 0 to 0,3 increase of calculation error is defined by inaccuracy of used approximation (1).

Thus, the method of calculation of regulation curve and attenuators nonlinear distortion at field-effect transistors with different gate structure is represented in the article. The coefficients of exponential-power-mode approximation for a number of JFETs are presented, calculated expressions for the components of equivalent source of current and for nonlinear transfer functions are represented. The mechanism of currents generation is considered and prevalent sources of nonlinearity are developed. The results of investigations of attenuators with parallel, series and combined connection of varied elements are given. It is shown that the discrepancy of calculated and experimental data of harmonic factor in the range of regulation of transmission coefficient 40 dB in the circuit of a parallel attenuator at MOSFET is not more than 20 %.

REFERENCES

1. Krivitskiy B.H., Saltykov E.N. System of automatic gain control. – Moscow: Radio and communication, 1982. – 190 p.
2. Bogdanovitch B.M., Vakser E.B., Okulitch N.I. Design of radio receiver elements (of controlled electron attenuators). – Minsk: Higher school, 1979. – 192 p.
3. Ignatov A.N., Ryanskiy A.I. The analysis of nonlinear properties of field-effect transistors in the area close to a cutoff // Radio engineering. – 1980. – № 9. – P. 36–38.
4. Bussgang J., Ehrman L., Graham J. Analysis of nonlinear systems multiple inputs // IEEE. – 1974. – № 8. – P. 1088–1119.
5. Zharkoi A.G., Tuev V.I. Approximation of MOSFET volt-ampere characteristics // Proceedings of High schools. Series of Radio electronics. – 1988. – № 5. – P. 69–70.
6. Zharkoi A.G., Tuev V.I. Approximation of volt-ampere characteristics of GaAs MESFETs with constant areas of negative resistance // Communication technology. Series of Radio measurement techniques. – 1988. – Issue 8. – P. 36–39.
7. Zharkoi A.G., Tuev V.I. The calculation of nonlinear equivalent sources of current of multioutlet active cells // Radio engineering and electronics. – 1989. – V. 34. – № 6. – P. 1142–1150.
8. Zi S. Physics of semiconductor devices. P. 1. – Moscow: Mir, 1984. – 453 p.

Arrived on 23.06.2006