the interval of modulation T_{mod}, and therefore overstatement of power-to-size ratio of frequency converter is minimal in this case.

Comparison of the results of analytical solution with the results of mathematical modeling by means of program package Orcad allows us to make a conclusion that maximal error of analytical solution is observed at values of Q factor Q<1,5. In this case the form of load current becomes different from the harmonic one, and form factors, calculated for harmonic curve, take another value.

Among the examined variants of control (fig. 5, 6) the latter (fig. 6) is the most perspective, as at equal conditions (parameters of load, pulses of line voltage) it provides minimal load current pulses.

To support sufficient accuracy of control it is recommended to apply PCM for FC in IHD, working in frequency range of 10 kHz and higher, as in this case, standard is completely satisfied.

It should be noted that PCM application in induction heating technique is new and very perspective area, as it allows virtually excluding dynamic losses for switching of power commutating devices at sufficient control accuracy. It could be supported by no other control modes, applied in induction heating.

REFERENCES

1. Voronov A.A. Basic of automatic control theory. – Moscow-Leningrad: Energiya, 1965. – 396 p.
2. Sluhotskiy A.E. Induction heating devices. – Leningrad: Energoisdat, 1981. – 325 p.
3. Dmitrikov V.F., Tonkal V.E., Grechko E.N., Ostrovskiy M.Ya. Theory and methods of analysis of frequency converters and key generators. – Kiev: Naukova dumka, 1988. – 312 p.
4. Solodovnikov V.V. Theory of engineering systems automatic control. – Moscow: N.E. Bauman's MSTU Press, 1993. – 492 p., ill.
5. Zinoviev G.S. Basic of power electronics. – Novosibirsk: NSTU Press, 2003. – 664 p.
6. Zypkin Ya.Z. Relay automatic systems. – Moscow: Nauka, 1974. – 575 p.
7. Shlyandin V.M. Digital measuring devices. – Moscow: Vysshaya schola, 1981. – 335 p.
8. Patanov D.A. General problems of switching loss enhancement in voltage inverters // Shemotehnika. – 2001. – № 7. – P. 17–19.
9. Dyudgy L., Pely B. Semiconductor power converters of frequency: Theory, characteristics, application. – Moscow: Energoatomizdat, 1983. – 400 p.
10. Chetty P. Design of key power sources. – Moscow: Energoatomizdat, 1990. – 240 p.
11. Kobzev A.V., Mihalchenko G.Ya., Muzychenko N.M. Modulation power sources of REA. – Moscow: Radio and communication, 1990. – 322 p.

Arrived on 05.07.2006

UDC 621.365.5

INVESTIGATION OF DEPENDENCIES OF RESONANCE CIRCUIT CHARACTERISTICS ON DESIGN AND ELECTRIC VALUES OF «INDUCTOR – HEATED OBJECT» SYSTEM

S.K. Zeman, A.V. Osipov, M.S. Saharov

FSSB «TSUCS RE automatics and electromechanics SRI»
E-mail: mikhaelf@mail.ru

The research of impedance characteristics of series resonance load circuit in the system of induction heating has been carried out. The border determination algorithm of resonance frequency change and tuned-circuit Q-factor at changing temperature of heating object, gap size between the inductor and the object, the number of windings and inductor current, nominal frequency is suggested.

Introduction

At present high-frequency induction heating is actively used in industry for wide spectrum of working operations. The source of magnetic field, causing heating of an element, is inductor. System «inductor-heated object» formed as a result of electromagnetic interaction with the element is a complex resistive-inductive load, which inductive character is compensated by a capacitor with formation of series resonance circuit, for frequency converter. The important peculiarity of induction heating systems is the dependence of the element electrophysical properties on its temperature, therefore during the process of heating complex impedance of «inductor-heated object» system and Q factor and frequency of resonance circuit are changed. Besides, these magnitudes depend on design and electric values of inductor system that is especially pronounced at heating of electromagnetic materials.

As a rule, for feeding of tuned circuit bridge circuit of resonance inverter is used, operating peculiarity of which is the system of phase-locked loop frequency control introduction, which parameters are determined to a large extent by such parameters of tuned circuit as resonance frequency, Q factor as well as these values turndown at heating. In this connection, the task of investigation and determination of tuned circuit parameters dependence on temperature, design and electric characteristics of inductor system is urgent. In spite of a number of papers [1–3], devoted to investigation of inductor system impedance characteristics, questions of calculations of required ranges of frequency control and change of resonance circuit Q factor are not investigated. Solution of this difficult problem is the aim of the given paper, in which the case of heating of ferromagnetic blocks at series connection of compensating capacitor with inductor is considered.

Mathematical model of the system «inductor-heating object»

The system «inductor-heated object» may be presented as equivalent circuit (fig. 1), which may be transformed to series connection of equivalent inductance L_{equ} and equivalent active resistance R_{equ}, which impedance may be found by well known formula [1]:

$$\dot{Z} = R_Э + j\omega L_Э;$$
$$R_Э = R_И + R_Д \frac{\omega^2 L_{ic}^2}{R_Д^2 + \omega^2 (L_Д + L_s + L_{ic})^2};$$
$$L_Э = L_{ic} \frac{R_Д^2 + \omega^2 (L_Д + L_s)(L_Д + L_s + L_{ic})}{R_Д^2 + \omega^2 (L_Д + L_s + L_{ic})^2}, \qquad (1)$$

where ω is the operating frequency, R_i is the active resistance of inductor windings, L_{ic} is the inductance of reciprocal interlocking, L_s is the leakage inductance, $R_Д$, $L_Д$ is the active resistance and inductance of heated object.

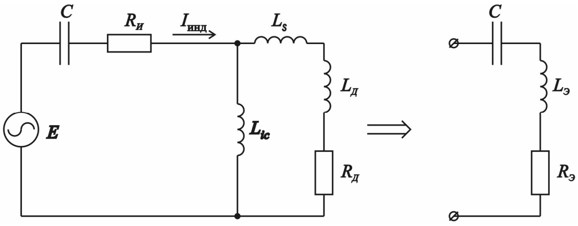

Fig. 1. *Equivalent circuit of the «inductor-heated object» system at series connection of compensating capacitor with inductor*

Inductance of reciprocal interlocking is stipulated by magnetic flux out of inductor, its calculation is difficult, first of all, because of irregular shape of field on this part of magnetic circuit. The problem of L_{ic} calculation for cylinders is solved by means of Nagaoke coefficient k introduction according to the formula [1]:

$$L_{ic} = L_0 \frac{k}{1-k}, \qquad (2)$$

where L_0 is the inductance of empty inductor:

$$L_0 = \frac{\pi D^2 \mu_0 W^2}{4l}, \qquad (3)$$

where D and l is the diameter and length of inductor, W is the number of its windings, μ_0=1,25·10^{-6} is the permeability of vacuum.

In engineering calculations Nagaoke coefficient is determined by ratios [2]:

$$k(D/l) = 0,224 + 0,756 \cdot \exp(-0,452\, D/l). \qquad (4)$$

Leakage inductance L_S includes magnetic flux in a gap between heated element and inductor and it is calculated by the formula [3]:

$$L_s = \frac{\pi \mu_0 W^2 (D+h)h}{l}, \qquad (5)$$

where h is the gap size.

Active resistance of a block is calculated by the formula [3]:

$$R_Д = \left(\frac{W}{l}\right)^2 S \sqrt{\frac{\omega \rho(\theta) \mu_0 \mu(H_0,\theta)}{2}}, \qquad (6)$$

where $\rho(\theta)$ is the specific resistance, S is the area of heated surface, $\mu(H_0,\theta)$ is the magnetic permeability of a medium, depending on field strength H_0 and temperature θ.

Dependence of magnetic permeability of bulk of carbon steels on temperature is determined by the ratio [3]:

$$\begin{cases} \mu(H_0,\theta) = 1 + \dfrac{\alpha \cdot H_0^{\beta} - 1}{\left(1 + \left(\dfrac{\theta}{\theta_K - \theta}\right)^{\chi}\right)^{\delta}}, & \theta \le \theta_K \\ \mu = 1, \quad \theta > \theta_K \end{cases}, \qquad (7)$$

where α=3·10^5, β=–0,85, χ=1,9, δ=0,16 are the coefficients, obtained as a result of electronic average experimental readings processing by the least-squares procedure [3], θ_K is the temperature, conforming to Curie point.

To calculate temperature dependence of specific resistance of object heated material in a first approximation we may use classical ratio [3]:

$$\rho(\theta) = \rho_0 (1 + \alpha_T \theta), \qquad (8)$$

where ρ_0 is the specific resistance at temperature 0 °C, α_T is the temperature coefficient of specific resistance.

Magnetic field strength is determined by the formula [3]:

$$H_0 = \frac{W I_0}{l}, \qquad (9)$$

where I_0 is the current amplitude through inductor.

Inductive and active resistances on the boundary of conducting medium are equal to [3], therefore inductance and active resistance of heated object is connected to the ratio:

$$R_Д = \omega L_Д. \qquad (10)$$

Thus, impedance characteristics of the system «inductor-heated object» depend on current, flowing through the inductor that significantly impedes calculation.

After impedance characteristics calculation tuned circuit capacity is calculated in terms of conditions of resonance operating condition with Q factor by the formula:

$$C = \frac{1}{\omega_p^2 L_{Э0} + \dfrac{R_{Э0}^2}{4L_{Э0}}}, \qquad (11)$$

where L_{e0}, R_{e0} are the values of L_e and R_e at environment temperature.

An attempt to express analytically resonance frequency of tuned circuit from the ratios (1–11) results in necessity to solve irrational equation, therefore, use of numerical procedures is reasonable.

Calculation of temperature dependences of resonance frequency and *Q* factor of series oscillatory circuit for the system «inductor-heated object»

At element temperature changing its electrophysical characteristics are changed, respectively depth of eddy currents penetration into heated object is changed. Depth of penetration, in its turn, determines proper frequency and Q factor of resonance circuit. Given circumstance significantly impedes calculation of temperature dependence of resonance frequency and Q factor, therefore irrational calculations are used for their design. Proposed algorithm of calculation of compensating capacitor capacity and dependence of resonance frequency and Q factor on temperature at constant inductor current is showed in figure 2. In the algorithm flowchart the following symbols are accepted: θ_{min} is the minimal temperature, equated to environment temperature, θ_{max} is the maximal temperature, $\Delta\theta$ is the temperature increment, f_{nom} is the nominal frequency (resonance frequency of a circuit at $\theta=\theta_{min}$), I_{stab} is the stabilized current amplitude, flowing through the inductor, f is the current value of frequency, $f_0(\theta)$ is the resonance frequency at preset temperature, ε is the maximal absolute error of frequency calculation, Q is the resonance circuit Q factor.

Dependences of resonance frequency and Q factor on temperature, obtained as a result of calculations by the algorithm (fig. 2) are showed in fig. 3. Dependences are plotted for the inductor with number of windings W=5 and geometries D=0,1 m, l=0,1 m, at gap size between windings of inductor and heated element h=5 mm, at f_{nom}=10 kHz and I_{stab}=1 кA.

The analysis of dependences obtained as a result of calculations (fig. 3) shows that at temperature near Curie point frequency and Q factor jumping is observed. In the case of changing of geometric and electric parameters of the system «inductor-heated object» qualitative character of dependences is retained. In practice, temperature dependences are characterized by more gradient junction through Curie point, since dynamic changes of material thermophysic properties are ignored.

Dependences of frequency control ranges and *Q* factor change on design and electric values of the system «inductor-heated object»

Resonance frequency control of tuned circuit at heating occurs automatically, therefore, for practical calculations of frequency transformers (FT) it is more important to determine extreme range of build parameters

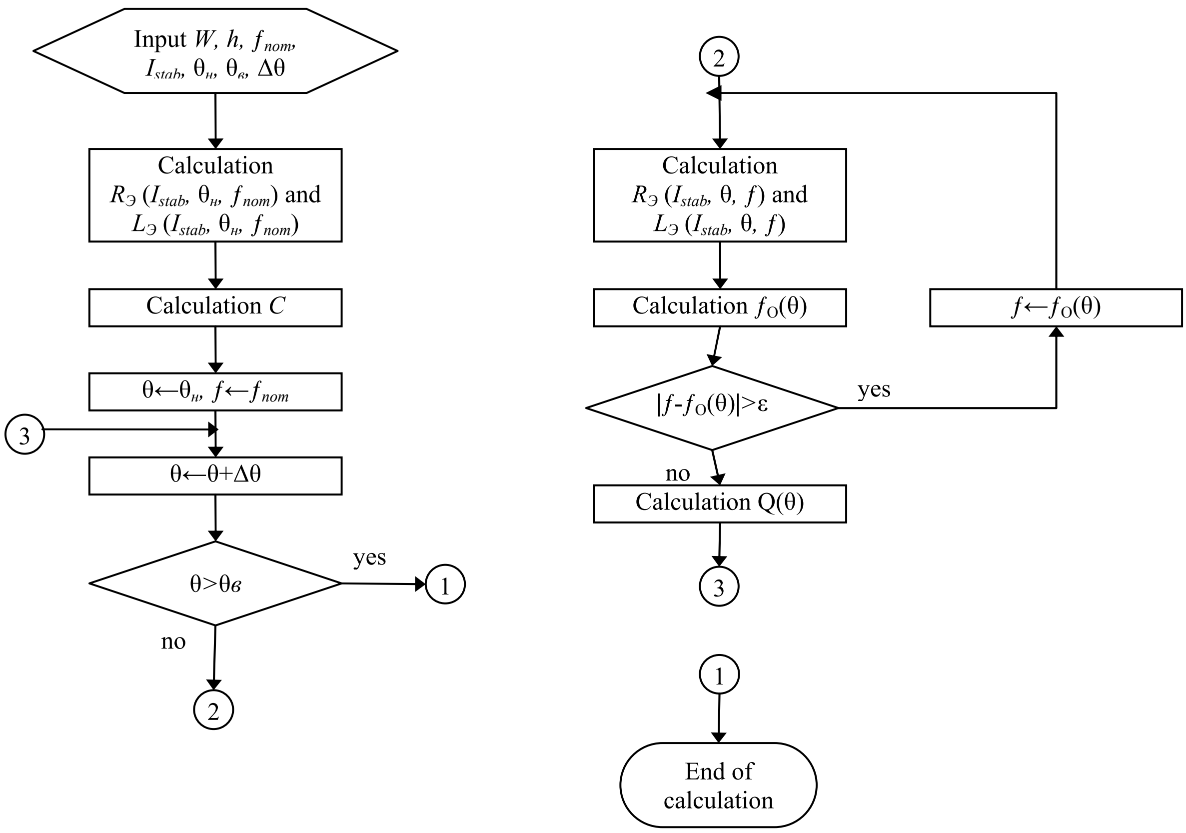

Fig. 2. *Computing algorithm of resonance frequency temperature dependences and Q factor of tuned circuit at specified values of* I_{stab}, f_{nom}, *h and W*

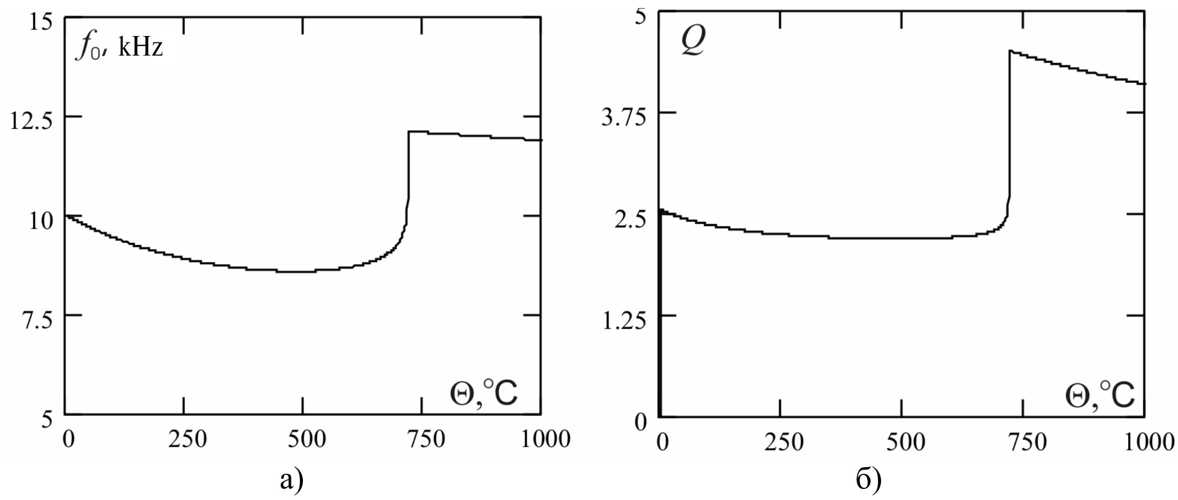

Fig. 3. *Temperature dependence of: a) resonance frequency; b) Q factor of tuned circuit at W=5, D=0,1 m, l=0,1 m, h=5 mm, f_{nom}=10 kHz and I_{stab}=1 кA*

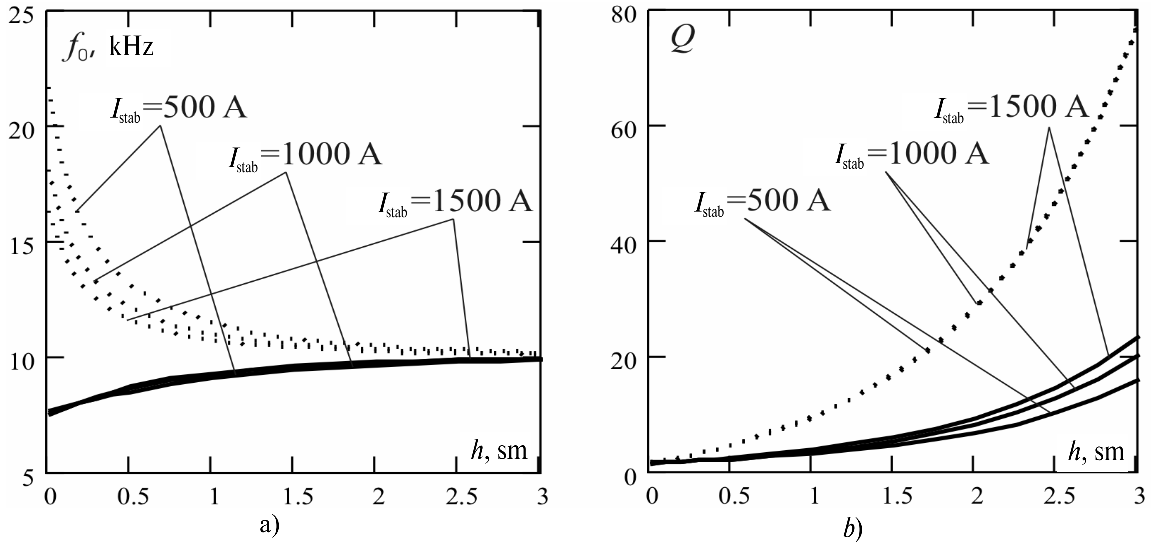

Fig. 4. *Dependence of turndown of: a) resonance frequency; b) tuned circuit Q factor on gap size between the inductor and the element at different values of I_{stab} and at W=5, D=0,1 m, l=0,1 m, f_{nom}=10 kHz*

change than their dependences on temperature. In practice, these parameters considerably depend on design and electric values of the system «inductor-heated object», specifically on gap size between the inductor and the element, determining leakage flux, inductor current, nominal frequency in initial conditions etc.

Schematic dependences of resonance frequency extreme values and Q factor of tuned circuit on gap size between the inductor and the element, obtained as a result of calculations by the algorithm (fig. 2) at different values of I_{stab} are presented in fig. 4.

It is seen from the presented results that at gap increasing frequency control range decreases and frequency range bounds approach to the nominal resonance frequency. It is explained by a significant increasing of leakage inductance at which element inductance change $L_Д$ does not influence appreciably equivalent inductance of the whole system. It should be noted that at inductor design engineers try to decrease the gap as much as possible, as it allows decreasing objective power of resonance capacitor. Dependence of frequency control range on inductor current is stipulated by decreasing of steel magnetic permeability with rise of inductor field strength according to (7). Upper bound of resonance frequency depends on inductor current, in spite of the fact that in the area of temperatures above Curie point μ=1. It is explained by resonance capacity changing by the data of prior nominal resonance frequency (10 kHz) retaining. Similarly the rise of Q factor with gap increase is explained; at h=0 Q factor does not change and is equal to one, as inductor system inductance is almost completely determined by the element inductance $L_Д$.

Q factor may be stated from the formulas (1), (10) by means of simple transformations:

$$Q = \frac{L_Д^2 + (L_Д + L_s)(L_Д + L_s + L_{ic})}{L_Д L_{ic}}.$$

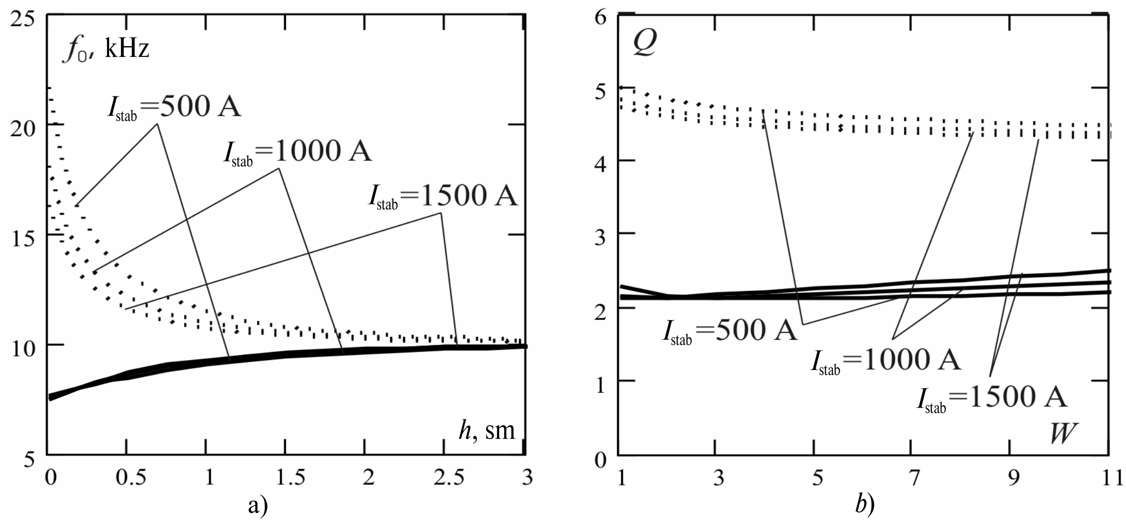

Fig. 5. *Dependence of changing boundaries of: a) resonance frequency; b) Q factor of tuned circuit on number of inductor windings at different values of I_{stab} and at h=0,01 m, D=0,1 m, l=0,1 m, f_{nom}=10 kHz*

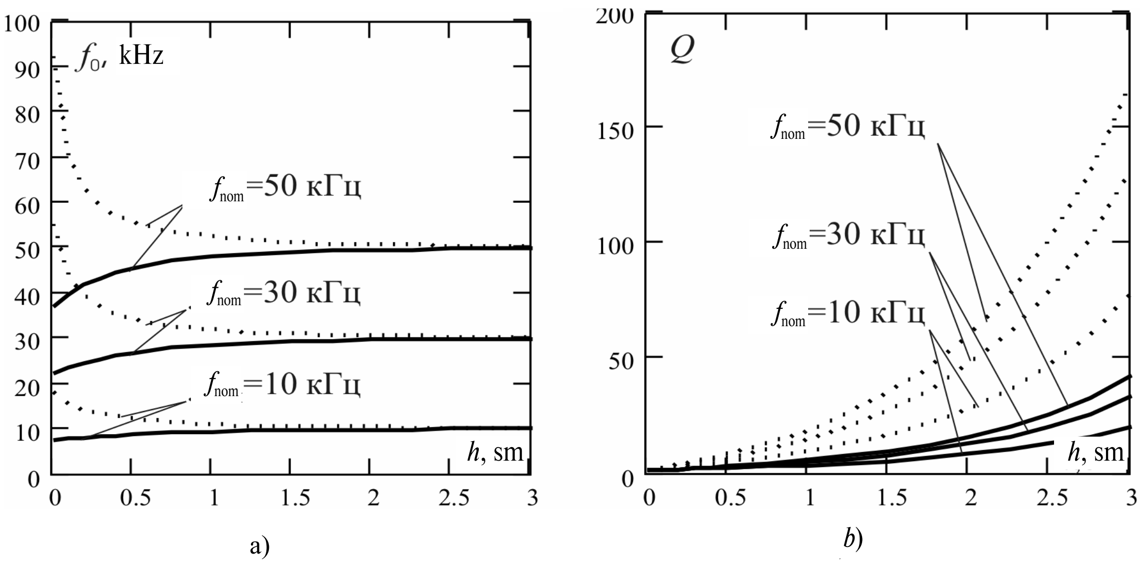

Fig. 6. *Dependences of changing boundaries of: a) resonance frequency; b) Q factor of tuned circuit on gap size between the inductor and the element at different values of f_{nom} and at W=5, D=0,1 m, l=0,1 m, I_{stab}=1 кА*

Usually L_{ic} is much more than $L_Д$ [2, 3], then

$$Q = \frac{L_Д + L_s}{L_Д} = 1 + \frac{L_s}{L_Д}. \qquad (12)$$

It follows from the expressions (5) and (12) that at h=0 Q factor Q=1 and does not depend on temperature of a block in the inductor, fig. 4, *b*.

Another important task is the investigation of changing of resonance circuit characteristics at variation of number of inductor windings. Schematic bounds dependences of trimming of tuned circuit resonance frequency and Q factor on number of windings of the inductor at h=0,5 sm are presented in fig. 5.

Characteristics (fig. 5, *b*) at small number of inductor windings may be not accurate, as stray flux increases. General tendency of frequency control range narrowing with increase of inductor winding density may be noted that results in rise of magnetic field strength in the inductor (9). In this case heating occurs at rather low values of magnetic permeability and properly, range of its changing decreases. Though, it does not follow from this that it is necessary to tend to maximal increase of winding density, as it results in voltage increasing at resonance capacitor.

Dependences of frequency control range and Q factor changing on h and for different values of nominal frequency f_{nom} at stabilized inductor current amplitude I_i=1 кА are considered further.

From the presented diagrams (fig. 6) significant increase of Q factor with frequency f_{nom} rise should be noted. It is explained by the fact that at frequency increasing, penetration depth of eddy currents in a block decreases, consequently, $L_Д$ decreases that at prior value of L_s results in Q factor rise according to the expression (12).

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:

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

where

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

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