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PULSE-CODE TECHNIQUE OF CONTROLLING PROCESS VARIABLE OF FREQUENCY CONVERTER IN INDUCTION HEATING DEVICE

S.K. Zeman, O.E. Sandyrev

FSSB «TSUCS RE automatics and electromechanics SRI»
*Tomsk Polytechnic University
E-mail: sandirev@mail.ru

The technique of pulse-code control of frequency converter process variable to install induction heating is suggested. The basic analytical relationships for calculation of control characteristics of the technique suggested at constant resistance of converter load are presented. Using the given method both loss power at switching power interconnecting device and mass-size parameters are shown to decrease significantly, whereas frequency converter efficiency increases.

Induction heating by high-frequency currents is the most modern and high-technology way of carrying out many working operations (element heating for pressing, hardening, crucible melting etc.) [1].

When designing processing equipment the wide range of powers, extracted at various elements, for providing required rate of their heating is necessary [2. C. 19]. Aforesaid, undoubtedly, requires application of controlling energy flux transmitted to the load in the devices of induction heating.

In up-to-date induction heating devices frequency converters (FC) with different control modes of process variable (current, voltage, power) are applied. One of the main disadvantages of known modes is a significant dynamic loss in key elements, occurring at controlling, that results, in its turn, in overheating and probable failing. This problem is solved by applying damping chain in this case FC circuit technology becomes more complex and their mass-size parameters become worth [3]. Therefore, at present, one of the main tasks of FC design is a choice of effective control mode, providing high efficiency and improving mass-size parameters of the developed device.

1. Systems with pulse-code controlling

Pulse-code systems [4], where forming of control action in a form of pulses set occur, are applied in control engineering. Systems with pulse-code modulation (PCM) have found wide application for power control in blast melting furnaces in the condition of average power leveling [5]. In SS P 51317.3.2-99 this method is determined as control of current alternation, i.e. the process of changing in relative of half-times of current flowing to the number of half-times, when there is no current.

Modification of this method is suggested to be used also in systems of induction heating, as at high values of Q factor of oscillatory circuit typical for these systems it allows controlling inductor continuous current with low pulses in wide range. For high-frequency systems of induction heating symmetric components of low-order consumed current, occurring in this case, meet the demands of SS P 51317.3.2-99, where it is noticed, that harmonic frequency should not be less than 40 harmonics of system voltage frequency (50 Hz), namely $f_{har.}$>2 кHz.

According to the conversion technique of control signal to control action [6] pulse-code controlling modes of FC are divided into main groups (fig. 1): with forward conversion analog-code, with programmed equilibrium and with following two-position conversion.

If at FC realization, the converter «analog-code» is selected as a controller, so sequence of control pulses (pulse-code combination), determined by the program beforehand, is assigned each value of control signal. Forward conversion allows obtaining high control rate.

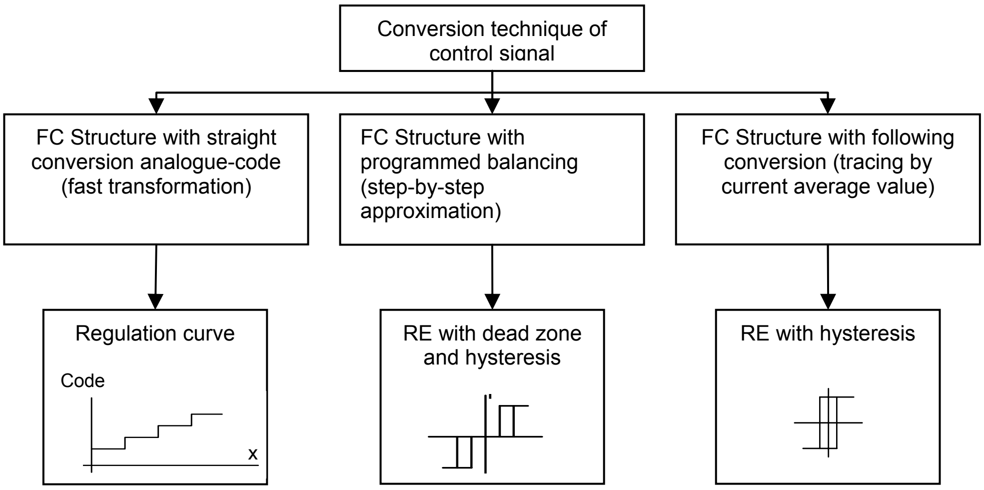

Fig. 1. *Techniques of conversion of control signal to FC of IHD*

At following conversion, comparison occurs uninterruptedly, the purpose of the process is output signal stabilization with accuracy defined by hysteresis size. In this case permission or prohibition at supply of each pulse of FC output voltage to inductor input is formed. The following systems are realized on the basis of relay element (RE) with hysteresis.

Programmed equilibrium conversion is characterized by step-by-step approximation of output signal to reference one [7]. In this case the RE with inert zone is applied, which forms transition to the next pulse-code control combination, antecedent combination or prohibits it. The process of conversion requires much more time than previous conversion techniques, due to necessity of several iterations, however it is more stable and reliable in operation. Accuracy at such conversion is defined by bounds of RE inert zone.

2. Theory of PCM

Standard scheme of FC with series-resonant voltage inverter is presented in fig. 2.

Control of average value of circuit energy at PCM is achieved by means of changing quantity of forcing pulses, connected with a load during some time period, called modulation period T_{mod} (fig. 3, *a*). Time period, within which inductor is connected to power supply, is called supply interval of forcing pulses T_{pul}. Interval, at which circuit load disconnection from power supply occurs, is called a free motion interval T_0. Frequency output of the inverter in this case is constantly tuned to resonance, so providing zero current of connection and disconnection of power commutating devices. Current flowing along the load remains continuous and has pulse

$$\Delta I = I_{\max} - I_{\min}. \quad (1)$$

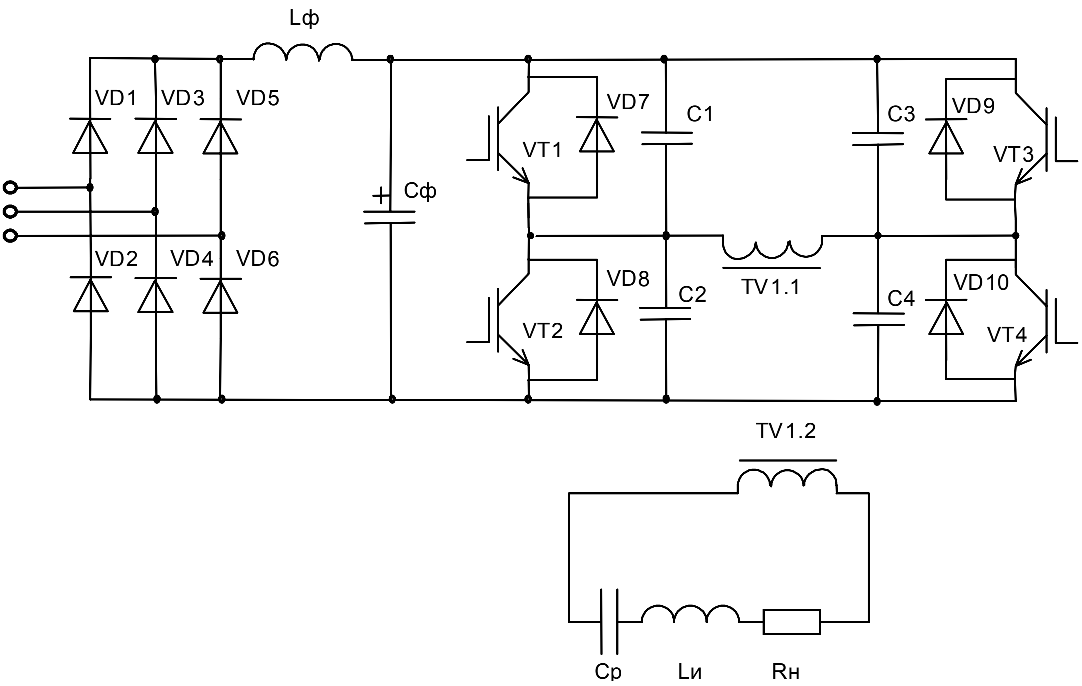

Fig. 2. *Standard scheme of FC with series-resonant voltage inverter*

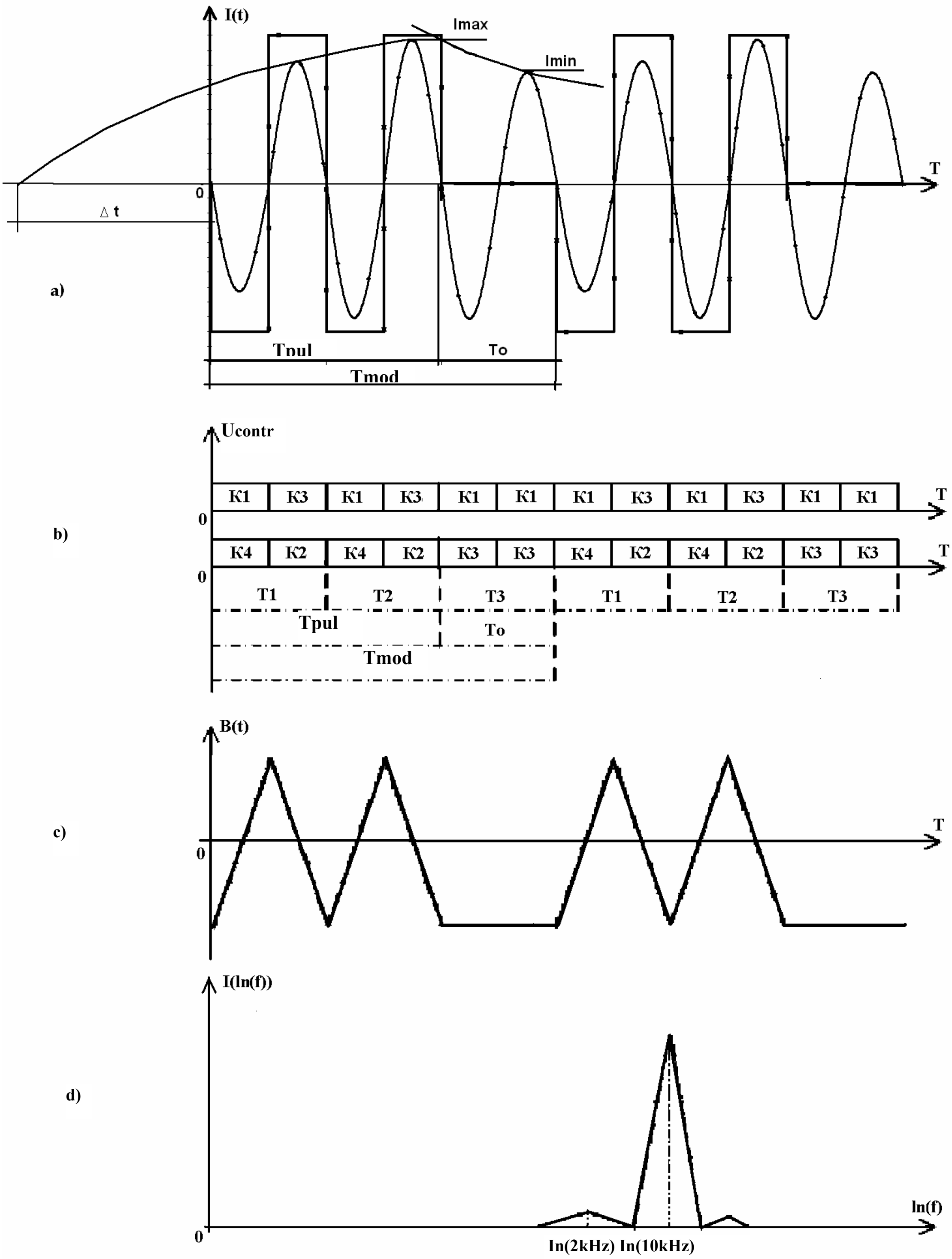

Fig. 3. *Diagrams of: a) voltage and current at FC output; b) control keys (K1, K2, K3, K4) at PCM; c) induction of matching transformer; d) spectral composition of load current $f_{har.}$>2кHz*

At low current pulses of inductor, power, extracted in the load during the modulation period also insignificantly changes and temperature of the load is determined according to a certain law, defined by its thermalphysic properties and average consumed power.

In comparison with frequency, pulse-width and frequency-pulse-width modulation of forcing pulses PCM does not result in phase shift between the output current and voltage, that increases power factor [8] and decreases dynamic losses in the scheme. Working induction of a transformer at control does not exceed its value in uncontrolled variant, fig. 3, *c*.

To defined regulation curve of PCM let us write down the expression of harmonic composition of rectangular voltage at FC output [9]:

$$u(\omega t)=\frac{2E}{\pi}\sum_{\nu=1}^{\infty}\frac{\sin(\nu\omega t)}{\nu}(1-(-1)^{\nu}), \qquad (2)$$

where E is the pulse amplitude of rectangular voltage at FC output, ν is a harmonica number, $\nu=1,2, ...$

Taking into consideration the fact that Q factor of series oscillating circuit $Q>>1$, let us calculate load current according to the first harmonica. In resonant mode, at $\nu=1$ we obtain:

$$i(\omega t)=\frac{4E}{\pi R}\sin(\omega t)=I_0\sin(\omega t). \qquad (3)$$

where R is the FC load.

In the interval T_{imp} (fig. 3, *a*) the envelope of current values of amplitudes of forced load current oscillation is described by the expression [10]:

$$I_m(t)=I_0(1-e^{-\delta(t+\Delta t)}), \qquad (4)$$

where $\delta=\frac{R}{2L}$ is the logarithmic decrement of current in resonant circuit LCR, t is damping time, Δt is time of coordinate origin shift for the envelope of current values of amplitudes of load current in stable conditions (fig. 3, *a*).

In the interval T_0 (fig. 3, *a*) the envelope of current values of amplitudes of load current free motion is written in the form:

$$I_m(t)=I_0(1-e^{-\delta(T_{имп}+\Delta t)})e^{-\delta(t-T_{имп})}. \qquad (5)$$

Proceeding from the condition of current amplitude balance at the point of time $t=0$ and $t=T_{mod}$, let us define Δt (fig. 3, *a*), equating right sides of expressions (4) and (5):

$$I_{\min}=I_0(1-e^{-\delta(\Delta t)})=I_0(1-e^{-\delta(T_{имп}+\Delta t)})e^{-\delta(T_{мод}-T_{имп})}. \qquad (6)$$

This implies that the expression of time shift of coordinate origin for the envelope of current values of amplitudes of load current in stable conditions Δt:

$$\Delta t=-\frac{1}{\delta}\ln\left(\frac{e^{-\delta(T_{мод}-T_{имп})}-1}{e^{-\delta T_{мод}}-1}\right). \qquad (7)$$

According to (4), the amplitude of load current in stable conditions will be maximal at the point of time $t=T_{pul.}$ and it will be written in the following way:

$$I_{m\max}=I_0(1-e^{-\delta(T_{имп}+\Delta t)}). \qquad (8)$$

In this case the amplitude of load current in stable conditions will be minimal, according to (5), at the point of time $t=T_{mod}$ and it is written in the form:

$$I_{m\min}=I_0(1-e^{-\delta(T_{имп}+\Delta t)})e^{-\delta(T_{мод}-T_{имп})}. \qquad (9)$$

Thus, pulse of loading current (ΔI) is written in the following way:

$$\Delta I=I_{m.\max}-I_{m.\min}=$$
$$=I_0(1-e^{-\delta(T_{имп}+\Delta t)})(1-e^{-\delta(T_{мод}-T_{имп})}). \qquad (10)$$

Taking into account the fact that

$$e^{-\delta\Delta t}=e^{\ln\left(\frac{e^{-\delta(T_{мод}-T_{имп})}-1}{e^{-\delta T_{мод}}-1}\right)}=\frac{e^{-\delta(T_{мод}-T_{имп})}-1}{e^{-\delta T_{мод}}-1},$$

let us rewrite the expression for pulses of loading current (10) in the form:

$$\Delta I=I_0\left(1-\frac{e^{-\delta T_{мод}}-e^{-\delta T_{имп}}}{e^{-\delta T_{мод}}-1}\right)(1-e^{-\delta(T_{мод}-T_{имп})}). \qquad (11)$$

Thus, taking into account the fact that $T_{imp}=\gamma T_{mod}$, the expression (11) is transformed to the form:

$$\Delta I=I_0\left(1-\frac{e^{-\delta T_{мод}}-e^{-\gamma\delta T_{мод}}}{e^{-\delta T_{мод}}-1}\right)(1-e^{-\delta T_{мод}(1-\gamma)}). \qquad (12)$$

where $\gamma=\frac{T_{имп}}{T_{мод}}$ is the duty factor.

Taking into consideration the fact that $e^{-\delta T_{мод}}=e^{-\frac{\pi}{Q}\nu}=\alpha^{\nu}$, where $\alpha=e^{-\frac{\pi}{Q}}$, and $\nu=\frac{T_{мод}}{T_0}$ is the order of modulation period with respect to the resonance period, let us rewrite (12) in the form:

$$\Delta I=I_0\left(1-\frac{\alpha^{\nu}-\alpha^{\nu\gamma}}{\alpha^{\nu}-1}\right)(1-\alpha^{\nu(1-\gamma)})=$$
$$=I_0\left(\frac{\alpha^{\nu\gamma}-1}{\alpha^{\nu}-1}\right)(1-\alpha^{\nu(1-\gamma)}). \qquad (13)$$

As in the system with pulse-code controlling in the load the harmonic current flows, and series oscillatory circuit is tuned to resonance and the load for resonance voltage inverter is active, when calculating the power balance the value of equivalent average current on the interval T_{mod}, which depends linearly on duty factor γ may be introduced. Then finite expressions for power calculation are also linear and simplify significantly the procedure of calculation of engineering design.

For calculation of amplitude value of equivalent average current on the interval T_{mod}, let us write the balance of power, consumed from the source of voltage and power, returning to the load:

$$P=I_{cp.cp}E_{cp}=I^2_{\partial\,cp}R, \qquad (14)$$

where $I_{cp.cp}=\frac{2}{\pi}I_{m.cp}$, $E_{cp}=E\gamma$ is a mean value of equivalent average current and supply voltage on the interval of modulation T_{mod}; $I_{\partial.cp}=\frac{I_{m.cp}}{\sqrt{2}}$ is the current value of the equivalent average current on interval of modulation T_{mod}.

From (14) we obtain the expression for amplitude value of equivalent average current on interval of modulation T_{mod}:

$$I_{m.cp}=\frac{4E}{\pi R}\gamma=I_0\gamma. \qquad (15)$$

Thus, the expression for calculation of power consumed from the source after substitution of (15) into (14) is written in the form:

$$P=\frac{8E^2\gamma^2}{\pi^2R}. \qquad (16)$$

At base value of power $\frac{8E^2}{\pi^2R}=1$ the regulation curve (16) has a form (fig. 4).

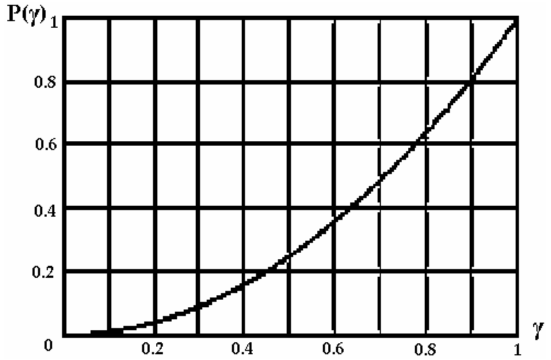

Fig. 4. *Regulation curve of PCM*

Normalizing the expression for loading current pulses in regarding I_0, we obtain:

$$\Delta I_0^* = \frac{\Delta I}{I_0} = \left(\frac{\alpha^{\nu\gamma}-1}{\alpha^{\nu}-1}\right)(1-\alpha). \qquad (17)$$

Having defined the magnitude of α for various values of Q factor, let us plot the set of curves $\Delta I_0^*=f(\gamma,Q)$ at ν=const (fig. 5, *a*).

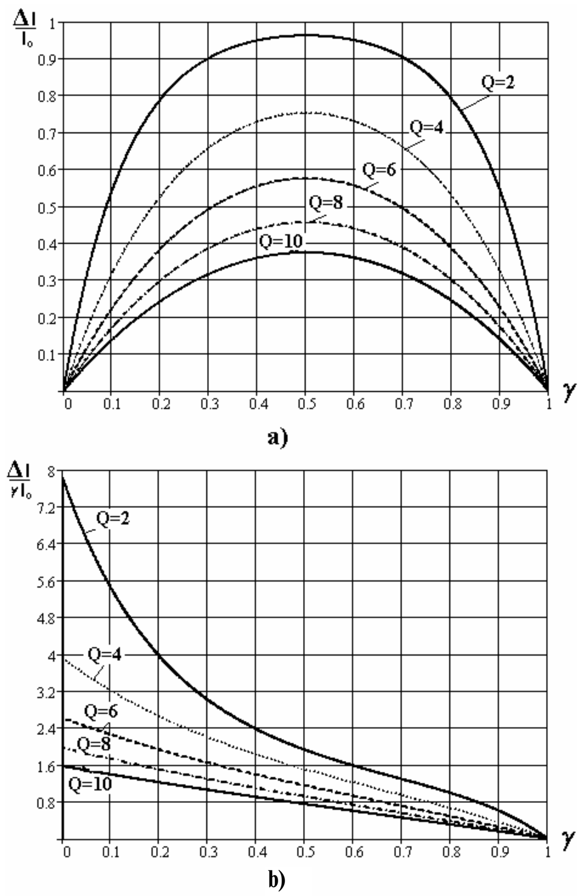

Fig. 5. *Set of curves: a)* $\Delta I_0^*=f(\gamma,Q)$ *b) at* $\Delta I_{cp}^*=f(\gamma,Q)$

Normalizing the magnitude of loading current pulses in respect to equivalent average value of current on the interval of modulation T_{mod}, we obtain the following expression:

$$\Delta I_{cp}^* = \frac{\Delta I}{I_{м.cp}} = \frac{1}{\gamma}\left(\frac{\alpha^{\nu\gamma}-1}{\alpha^{\nu}-1}\right)(1-\alpha). \qquad (18)$$

Having defined similarly magnitude α for various values of Q factor let us plot the set of curves $\Delta I_{cp}^*=f(\gamma,Q)$ at ν=const (fig. 5, *b*).

Regulation curves, fig. 5, correspond to dependences of current relative pulses of oscillatory circuit at various values of duty factor γ and Q factor Q, and also at modulation constant period (ν=const).

It is possible to minimize pulses, using abilities of modulation period variation at realization of practical control algorithm. Let us consider the changes in regulation curves at variable modulation period (ν=var) and constant quantity gaps of resonance current periods.

Minimal current pulses are observed at gap of one resonant period of load current. To obtain the set of curves, conforming to this mode of operation, let us define duty factor (γ), by the order of modulation period (ν):

$$\gamma = \frac{T_{\text{mod}}-T_0}{T_{\text{mod}}} = \frac{\nu T_0 - T_0}{\nu T_0} = \frac{\nu-1}{\nu}. \qquad (19)$$

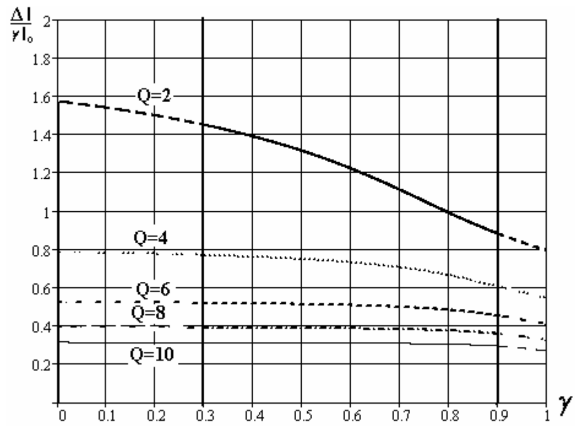

Fig. 6. *Set of curves:* $\Delta I_{cp}^*=f(\gamma,Q)$

Then the expression for pulses of loading current relative to equivalent average value of current on the interval of modulation T_{mod} in the function in terms of duty factor (γ) has the form:

$$\Delta I_{cp}^* = \frac{1}{\gamma}\left(\frac{\alpha^{\frac{\gamma}{1-\gamma}}-1}{\alpha^{\frac{1}{1-\gamma}}-1}\right)(1-\alpha). \qquad (20)$$

The set of curves, conforming to the condition of miss of one resonance frequency period is presented in fig. 6. It should be noted that the given set of curves has quite specific range of duty factor (γ) change. The low bound of this range (γ=0,3) conforms to pulse-code combination of one half-period of injecting and one period of gap.

It is seen in fig. 6 that loading current pulses are significantly nonlinear at low values of Q factor of oscillatory circuit (Q<2), it follows from this that application of PCM in high-Q circuits is appropriate. In this case the form of load current is approximated as much as possible to the equivalent average value of current in the

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.

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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