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METALLURGICAL EQUIPMENT

Induction Heating Plant for Heat Treatment of Spherical Metal Products

V. N. Meshcheryakov and S. S. Titov

Lipetsk State Technical University, Lipetsk, Russia

e-mail: algebra934@yandex.ru

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Abstract—A control system for an induction heating plant is developed and studied to perform symmetric high-rate surface induction heating of spherical metal products with given technological parameters for heat treatment.

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INTRODUCTION

To create energetically efficient continuous-action equipment for symmetric heating of spherical metal products to a given depth for heat treatment without oxidation and decarburization is a challenging problem for some industries, including the mass production of milling bodies for ore-dressing and processing enterprises and cement plants, balls for rolling bearings and valves in hydraulic systems, and wear-resistant balls in the backwater gates of deep-well pumps for oil production.

Induction heating with direct high-rate (several seconds or fractions of a second) conversion of electric energy into heat energy meets these industrial heating requirements best of all. This method of heating is characterized by simple temperature and heating depth control, which makes it possible to obtain the optimum combination of a high surface hardness (back-to-back endurance) of products with a relatively plastic core (anticracking) after quenching and tempering.

However, despite all advantages of this method, it is only applied to produce articles of a continuous or near-continuous cross section with ensured symmetry of heating in the world practice. To develop a control system for an induction heating plant (IHP) to ensure high-quality heating of spherical metal products seems to be a challenging problem.

ENSURED SYMMETRIC HEATING

To solve the problem of symmetric induction heating of spherical metal products, we [1, 2] proposed a new configuration for a work-coil, the guiding chute (i.e., conveying chute) of which is bent to form a spatial spiral with a vertical axis of symmetry (Fig. 1).

The kinematics of ball motion along the spiral chute in the work-coil (free motion) is characterized by two-dimensional, or three-dimensional at a variable curvature of spiral coils (or the motion trajectory of the center of ball mass), stimulation to changing the axis of ball rotation from the entrance into the work-coil to the exit from it. This fact implies the possibility of creating continuous IHP that provides density-uniform interaction of the entire ball surface with the electromagnetic field in the work-coil and, correspondingly, the possibility of reaching symmetric heating to a given depth. This heating is direct, high-rate, and energetically efficient with very weak oxidation and decarburization.

IHP CONTROL SYSTEM

From the standpoint of operation of induction plants, the following two methods of controlling an electric regime are possible [3]:

(i) stabilization of the voltage across a load U_l (this regime is applied in surface quenching plants and methodic heaters, where the heating of periodically changed workpieces should be repeated),

(ii) stabilization of dc link current I_d at a nominal level $I_{d\text{nom}}$.

The latter regime is applied in melting plants, since it ensures the maximum power consumption $P = U_{d\text{nom}} I_{d\text{nom}}$ and, hence, the maximum heating and melting of a metal.

The stabilization of the voltage across a load U_l or its change according to a certain law can be ensured by the following two methods [3]:

(a) change in dc link voltage U_d,

(b) control of angle φ between output voltage U_l and current I_l of an inverter.

The circuit proposed in [4] has the widest control possibilities (Fig. 2a). In this circuit, work-coil current I_l is maintained by controlling the following two

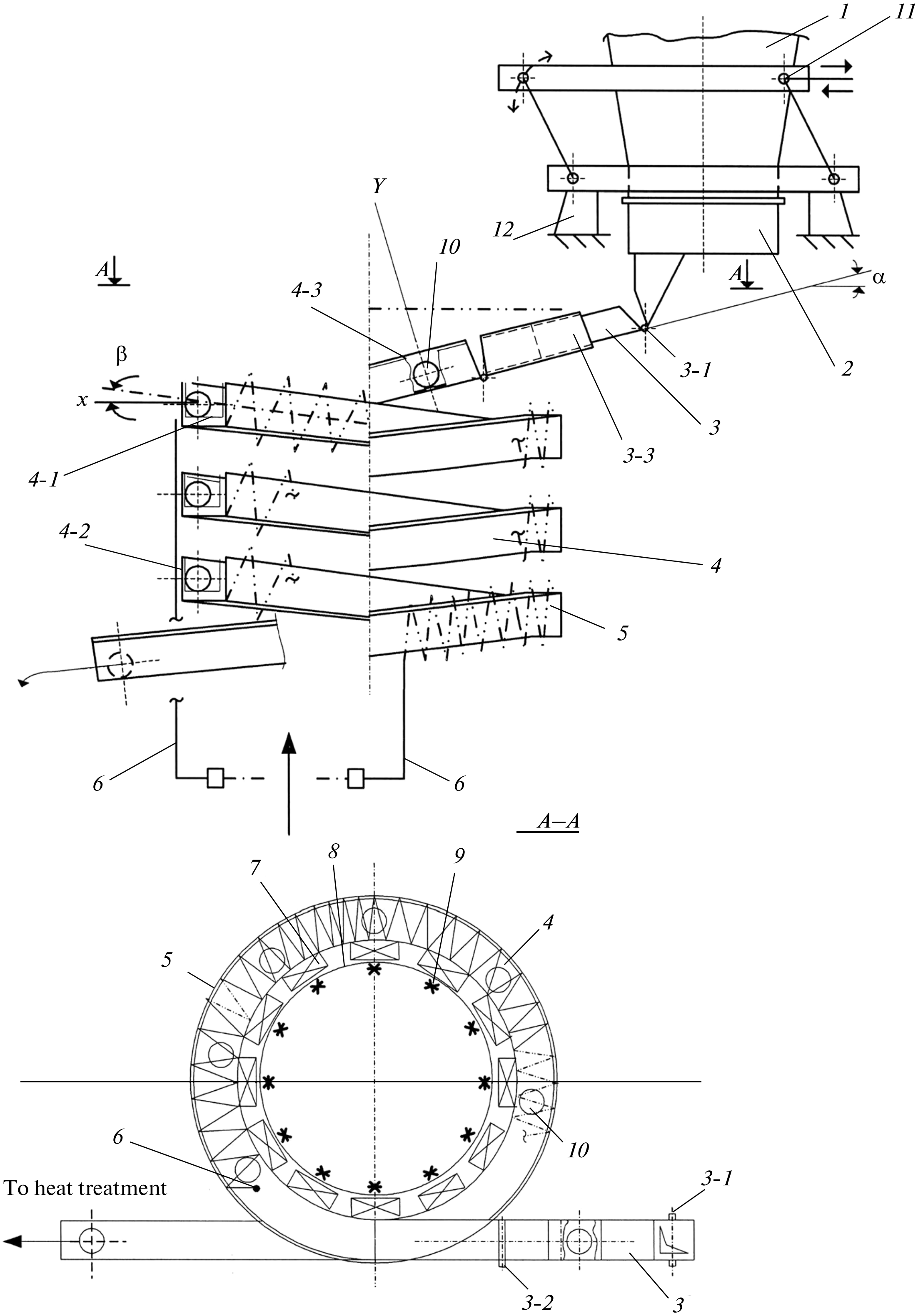

Fig. 1. Continuous plant for symmetric induction heating of spherical metal products: (*1*) service bunker; (*2*) underbunker discrete feeder; (*3*) guiding chute; (*3-1*, *3-2*) articulated joints; (*3-3*) telescopic joints; (*4*) transporting work-coil profile; (*4-1*) link rail of profile; (*4-2*) external vertical wall; (*4-3*) straight profile segment in induction solenoid coil at ball input; (*5*) work-coil solenoid contour; (*6*) current leads; (*7*) magnetic cores; (*8*) spacing hoop; (*9*) compression screws; (*10*) article to be heated; (*11*) parallelogram mechanism for bunker displacement; and (*12*) supporting structure.

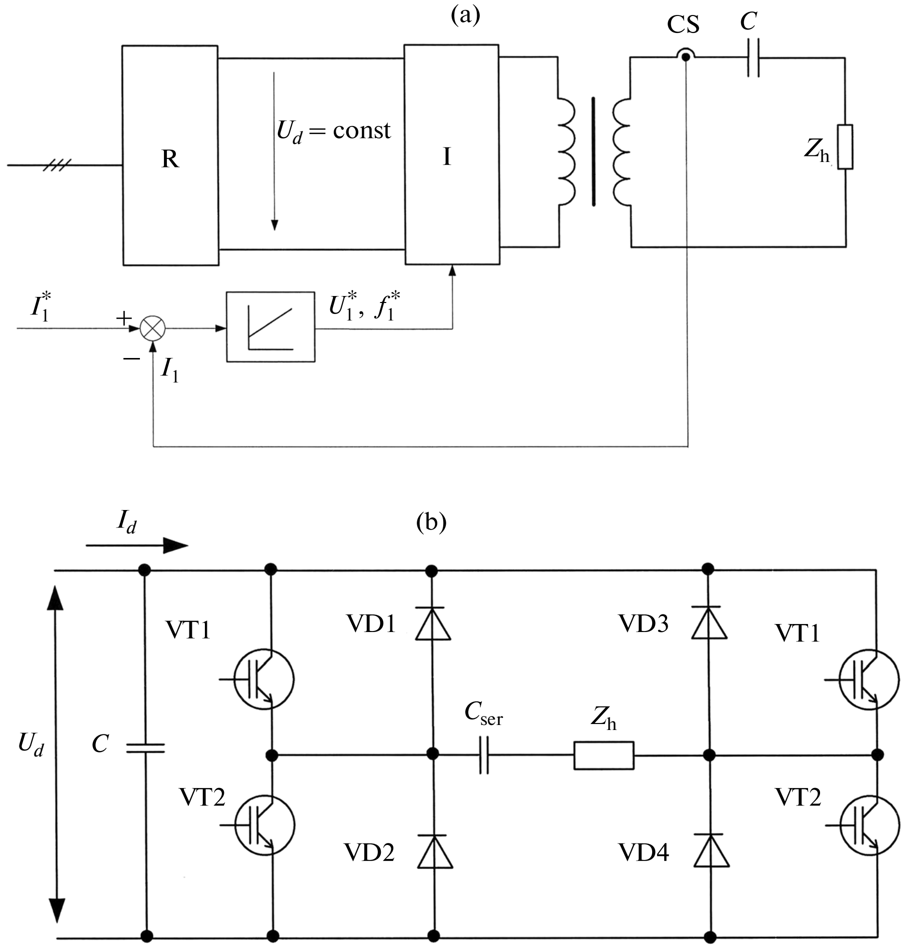

Fig. 2. (a) Voltage and frequency control circuit (R, controlled rectifier; I, inverter; CS, current sensor; Z_h, work-coil) and (b) SRI circuit based on IGBT transistors (VT1–VT4) with free-wheeling (VD1–VD4) diodes (U_d, I_d, rectified voltage and current; C_{ser}, in-series capacitance).

parameters: inverter frequency f and output voltage U_1. This circuit makes it possible to stabilize a given electric regime for a load with variable parameters. One of the examples of application of the control circuit is to maintain the output inverter power at a constant level (Fig. 2a). It is known [5] that the active resistance of the circuit decreases substantially (severalfold) as the workpiece temperature increases, which results in a sharp increase in the output inverter power. Therefore, the output power is limited by introducing a current or power feedback.

The developed circuit makes it possible to limit the power at a given level by decreasing output voltage U_1. Output frequency f in this case can remain constant and the inverter can operate at an angle $\varphi = 0$.

As the most proper electric circuit of the inverter in IHP, we chose a self-commutated resonance inverter (SRI) based on IGBT transistors with free-wheeling diodes; its electric circuit is shown in Fig. 2b [4].

To develop a control system for SRI to maintain specified technological parameters of heating metallic balls, we have to know the character of the electromagnetic transient processes that occur when a ball passes through the work-coil. One of the main parameters that determine the character of the electromagnetic transient processes is the position of a ball in the work-coil at any time. In turn, the position of a ball in the work-coil depends on various external forces of both electromagnetic and mechanical nature. Therefore, it is necessary to develop a combined model to take into account all possible factors affecting the ball motion.

To develop a mathematical model, we determined the parameters of the equivalent circuit of the work-coil as a function of the position of a ball in it (Fig. 3a). The relationships that exist for the calculation of the equivalent circuit parameters are presented for the case of a cylindrical workpiece in the work-coil [5]. To simplify calculations, bodies of various shapes in the work-coil are represented in an equivalent cylindrical shape [6]. Let us represent a metallic ball as an equivalent cylinder. To this end, a ball is divided into n ele-

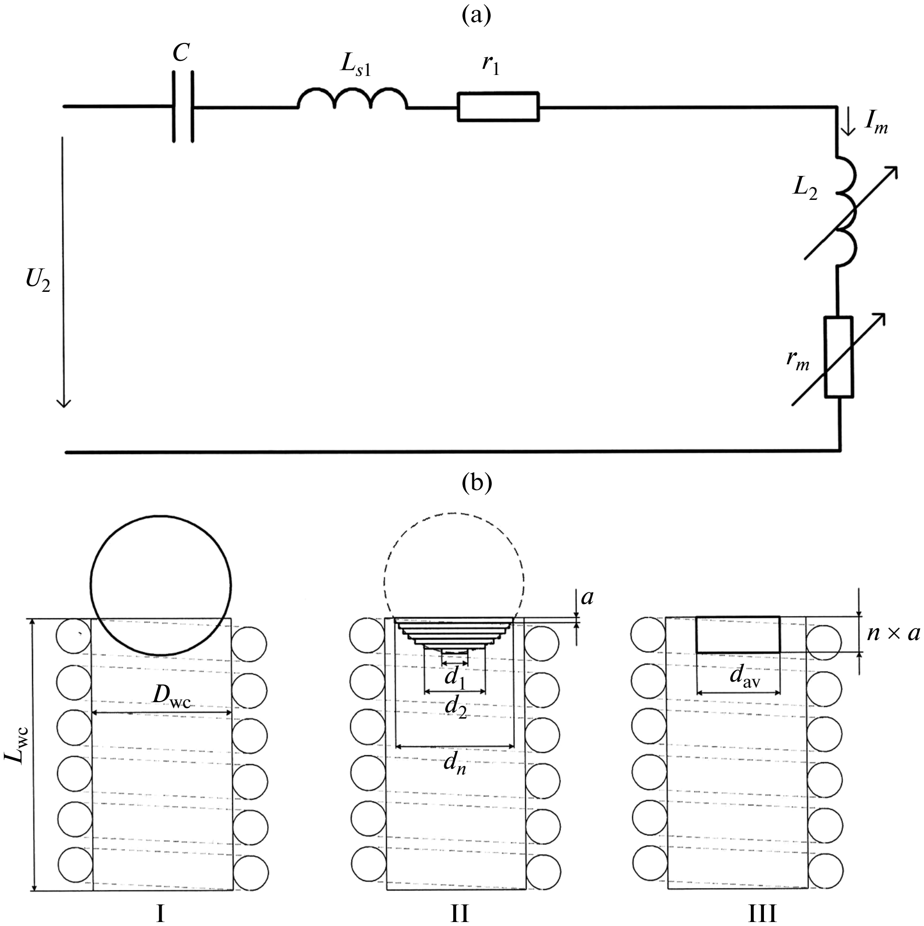

Fig. 3. (a) Equivalent circuit of the work-coil: r_1 is the active resistance of the work-coil conductors; L_{s1} is the inductance of the work-coil conductors; C is the auxiliary capacitance of the circuit; L_2 and r_m are the variable inductive reactance and active resistances of the work-coil charge, respectively; U_2 is the work-coil voltage; and I_m is the magnetization current. (b) Representation of a ball as an equivalent cylinder: D is the ball diameter, L_{wc} is the work-coil segment length, and d_{av} is the average diameter of the equivalent cylinder. (I) Image of a ball and the work-coil segment, (II) division of the bal into elementary cylinders, and (III) representation of the ball as an equivalent cylinder.

mentary cylinders with different diameters d_n and the same height (Fig. 3b).

The parameters of the equivalent circuit for the equivalent cylinder in the work-coil are determined as follows [5]:

$$\begin{cases} r_m = cr'_m = c\dfrac{W^2\pi\rho d_{av}}{\Delta_h na}; \\ L_2 = cL'_2 = \dfrac{c}{2\pi f}\left(r'_m + X_{s2} + \dfrac{(X_{s2} + r'_m)^2 + (r'_m)^2}{X_0}\right), \end{cases} \quad (1)$$

where r'_m and L'_2 are the values of r_m and L_2 that are not reduced to the current of a work-coil of a finite length, W is the number of inductor coils, f is the work-coil current frequency, ρ is the electrical resistivity of the ball material, Δ_h is the active heating depth, c is the reduction coefficient, X_{s2} is the reactive scattering resistance calculated for a homogeneous field, and X_0 is the reactive resistance that determines the magnetizing force component that is required for a magnetic flux to overcome the space outside the work-coil.

The main problem of the SRI control system is to maintain the given technological parameters of induction heating of balls, i.e., the specific power supplied to the surface of the article to be heated and the active heating depth [5].

Active heating depth in a ball Δ_h is determined by the surface effect and depends on work-coil current frequency f and the properties of the ball material,

$$\Delta_h = \frac{1}{\sqrt{\pi f \mu_0 \mu \dfrac{1}{\rho}}}, \quad (2)$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability of vacuum, μ is the relative magnetic permeability, and ρ is the electrical resistivity.

The electrical resistivity of carbon steels is known to depend on temperature, and their relative magnetic permeability depends on temperature and, correspondingly, magnetic field H [7].

The technological parameters of heating can be controlled by changing the electric parameters of the inverter. These parameters are U (effective value) and inverter output voltage frequency f. As follows from the relation between these two parameters, several methods of controlling the inverter output energy exist. One of the most widely used methods for controlling the inverter output energy is frequency modulation (FM) of the output voltage. In this case, the voltage remains constant and the output current is controlled by changing frequency, i.e., by increasing the reactive component of the circuit impedance when frequency goes from the resonance frequency.

Another control method is pulse-duration modulation (PDM) of the output voltage. PDM is performed via a phase shift (through a certain angle) the control signals of transistors in one inverter arm with respect to the other. The voltage in this case depends on the phase shift and the voltage frequency is specified independently. The output current depends on both the output voltage amplitude and frequency.

As for the IHP under study, it is reasonable to apply the second control method, since it provides two inverter control channels. Therefore, the problem to be solved by the control system is to calculate the output voltage amplitude and frequency as functions of given specific power P_{h}^{*} and given active depth Δ_{h}^{*} upon heating a ball.

SRI operates at output voltage frequencies close to the resonance frequency of the circuit. In this case, the circuit is represented by the equivalent circuit of the work-coil shown in Fig. 3. The equivalent circuit is characterized by a change in inductance L_2 over a wide range when a ball passes through the work-coil, which results in a significant change in the resonance frequency of the circuit f_{res}. Therefore, for the inverter to work, the output inverter frequency should be permanently adjusted to be close to the resonance frequency. In the existing induction heating systems, this adjustment is performed with phase locking (PL) [8]. The principle of PL consists in the maintenance of the frequency at which the phase shift between the output current and voltage is zero, i.e., the frequency at which the reactive component of the circuit impedance is zero.

As for the plant under study, PL cannot be used to control the inverter frequency as a function of a given active heating depth in a ball; that is, the possibility of controlling one of the specified technological parameters disappears. It is more reasonable to use the method at which circuit resonance frequency f_{res} is continuously calculated. In addition, the required frequency is calculated as a function of given active heating depth (f_Δ) and the inverter output frequency is determined using these two values.

The resonance frequency can be continuously calculated as follows. Work-coil voltage $\dot{U}_{2lm}$ (in vector form) can be measured with a voltage sensor,

$$\dot{U}_{2lm} = j2\pi f L_{s1}\dot{I}_m + r_1\dot{I}_m + \dot{U}_{2m}. \tag{3}$$

Work-coil current $\dot{I}_m$ is measured with a current sensor. Therefore, total resistance $\dot{Z}_m = r_m + jL_2$, which depends on the position of a ball in the work-coil, can be calculated,

$$\dot{Z}_m = \frac{\dot{U}_{2m}}{\dot{I}_m} = \frac{\dot{U}_{2lm} - \dot{I}_m(j2\pi f L_{s1} + r_1)}{\dot{I}_m}. \tag{4}$$

When measuring phase shift α_m between voltage $\dot{U}_{2m}$ and current $\dot{I}_m$ and their amplitudes $U_{2m\mathrm{A}}$ and $\dot{I}_{m\mathrm{A}}$, we can determine r_m and L_2,

$$\begin{cases} r_m = \dfrac{U_{2m\mathrm{A}}}{I_{m\mathrm{A}}}\cos a_m; \\ L_2 = \dfrac{U_{2m\mathrm{A}}}{2\pi f I_{m\mathrm{A}}}\sin\alpha_m. \end{cases} \tag{5}$$

The resonance frequency of the circuit is

$$f_{\mathrm{res}} = \frac{1}{2\pi\sqrt{(L_{s1} + L_2)C}}. \tag{6}$$

The current power consumed for heating a ball can be written as

$$P_m = I_m^2 r_m. \tag{7}$$

Therefore, work-coil current I_m should be controlled to control the ball heating power.

Based on Eqs. (1)–(7), we developed a system for controlling the inverter; its schematic diagram is shown in Fig. 4. The output current amplitude is controlled with a proportional–integral (PI) controller, the output of which influences the output voltage of the inverter. The voltage in the proposed SRI control system is controlled by changing the pulse width. Figure 5a shows an oscillogram of the inverter output voltage. The current is calculated from the given specific heating power. For this purpose, a ball, which is preliminarily heated to the average temperature of the work-coil segment where it is situated, is placed in a

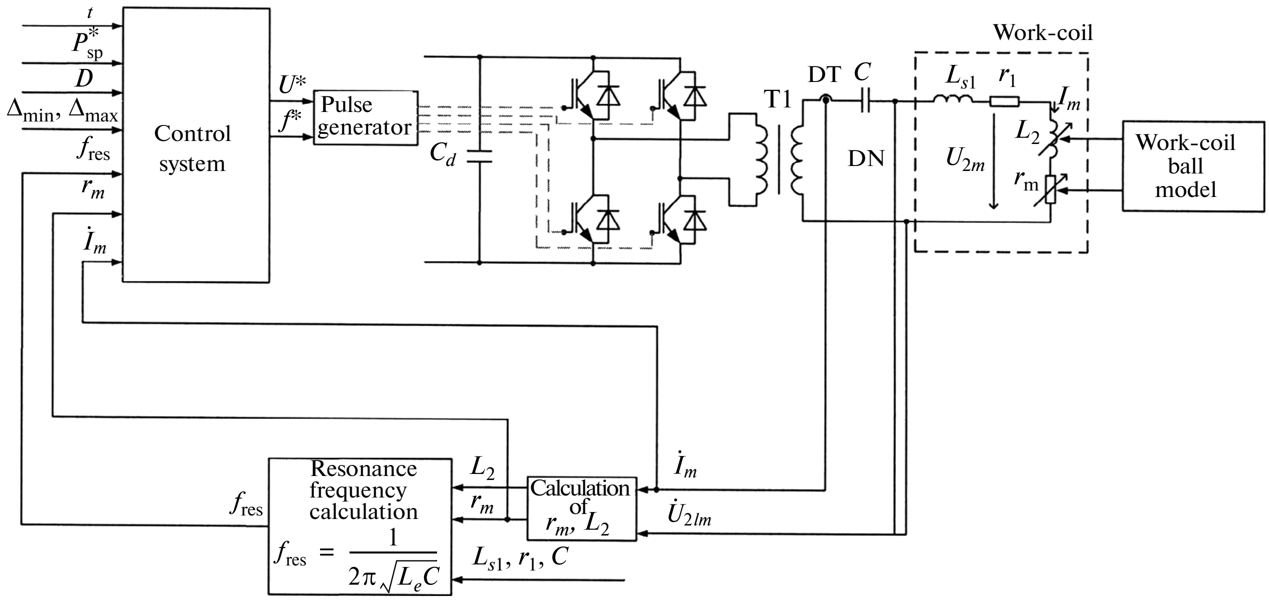

Fig. 4. Control system of the self-commutated resonance inverter in an electrotechnical plant for symmetric induction heating.

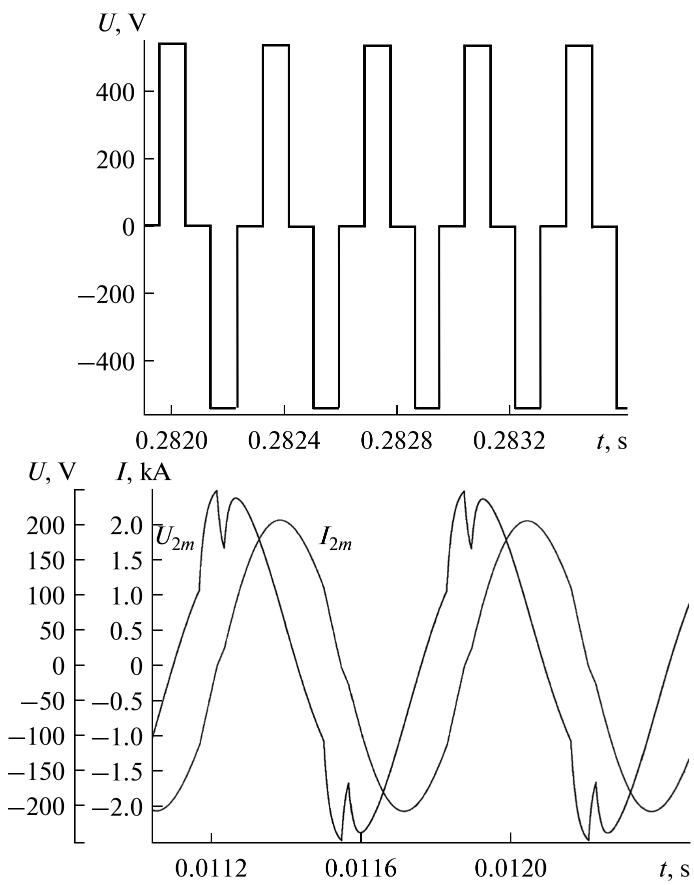

Fig. 5. (a) Output inverter voltage and (b) work-coil voltage and current.

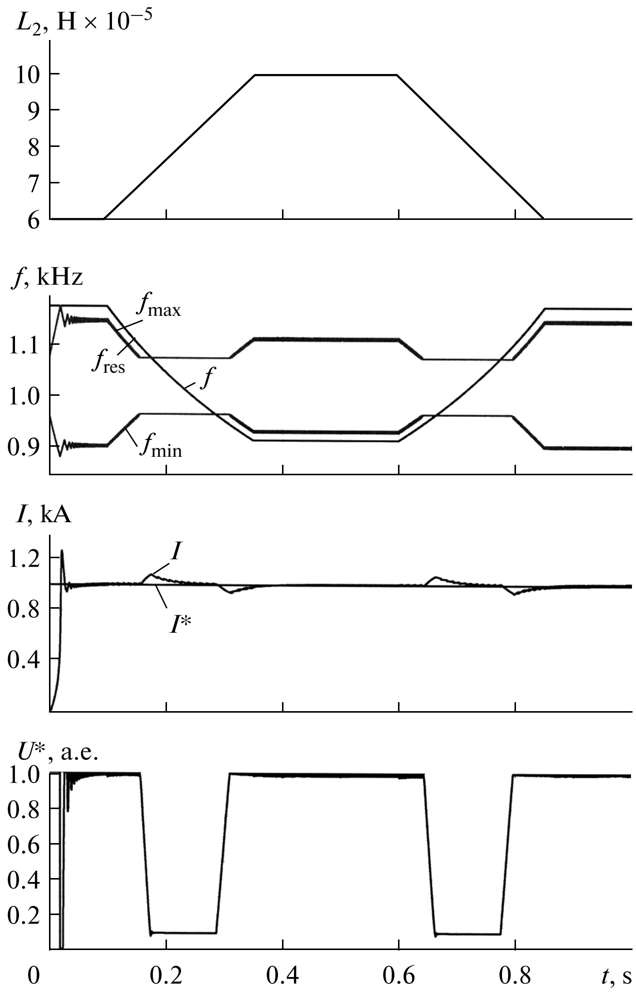

Fig. 6. Transient process curves when a ball passes through the work-coil.

work-coil. A small current then passes through this segment and resistance r_m is measured. The specified current amplitude is then constant, $I^*_{mA} = \sqrt{\dfrac{2P^*_{sp}}{\pi D^2 r_m}}$.

The output frequency of the inverter is preset to be equal to calculated resonance frequency f_{res} with allowance for limitation on the minimum and maximum values. These values are determined from the given active heating depth range. When the resonance frequency goes outside the limitation, the inverter operates at the limited frequency, and the output current amplitude is still controlled by the PI controller. If the resonance frequency changes to the value at which the PI controller reaches the output limitation, which is the maximum output voltage, it becomes impossible to maintain a given output current in the system.

This case is impossible when a ball with a high magnetic permeability (the temperature and the magnetic field are such that μ is close to the maximum value) passes through the work-coil, when the inductances of the empty and filled work-coils differ substantially. To maintain a given heating power is a more important problem than to ensure a given active heating depth because of heat conduction. Therefore, it is necessary to maintain a given output current. To this end, an I controller is added to the system to correct the inverter output frequency limitations. This controller begins to operate when the PI controller limitation is reached and increases the output frequency limitations.

In this case, frequency modulation is actually performed: the output voltage is constant and maximal (PI controller in the limitation) and the output current is controlled by changing the output frequency (the inverter output frequency is equal to the limitation frequency).

Figure 5b shows instantaneous work-coil voltage and current curves. Figure 6 shows the transient processes that occur in the system when one ball passes through the work-coil. The active heating depth is specified in the range 0.36–0.38 mm; therefore, the frequency limitation range here is rather small. The frequency limitation becomes operative when the work-coil is empty or the entire ball comes in the work-coil. Since the PI controller reaches limitation, a given current is maintained by correcting the frequency limitation using the I controller. In this case, the real active heating depth goes outside the given range.

CONCLUSIONS

We developed a control system for a self-commutated resonance inverter to control the following technological parameters of IHP for symmetric induction heating of metallic balls: the power and the active heating depth in a ball. The results obtained can be used in enterprises producing the spherical metal products that operate under heavy conditions caused by impact and other types of loading of contact surfaces. First of all, these products include milling balls (beneficiation of iron ore in ore-dressing and processing enterprises) and balls for rolling bearings of various types and sizes. The dynamic characteristics of IHP, which manifest themselves when a ball passes through a work-coil, were studied. Our results can be used for designing new high-frequency current induction heating plants.

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