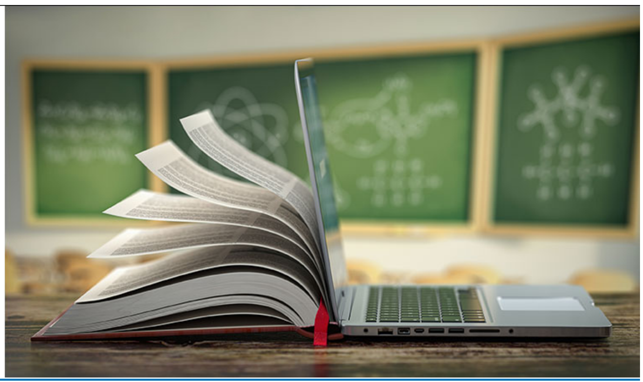
PAPER • OPEN ACCESS

Energy-efficient installations of multi-zone multi-frequency induction heating of steel billets for large deformation

To cite this article: V I Lusgin *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **950** 012009



IOP Conf. Series: Materials Science and Engineering **950** (2020) 012009 doi:10.1088/1757-899X/950/1/012009

Energy-efficient installations of multi-zone multi-frequency induction heating of steel billets for large deformation

V I Lusgin[1], I E Lopatin[1,3], E P Shalina[1], A Y Petrov[2], S M Fatkhullin[2], I G Alekseev[2]

[1] High-Voltage Engineering Department, Ural Power Engineering Institute, Ural Federal University, 620002, building 5, Sofia Kovalevskoy str., Ekaterinburg, Sverdlovsk region, Russia
[2] OOO NPP «RELTEC», 620078, building 51A, Studencheskaya str., Ekaterinburg, Sverdlovsk region, Russia

Abstract. This article discusses the basic construction principles of the device for multi-zone induction heating. The mathematical model of a cascade inverter is described. Various modes of heating cylindrical billets are considered depending on the ratio of powers in the heating zones and current frequencies in the inductors. The indicators of heating uniformity over the cross section and energy efficiency are studied. Based on the data obtained, a conclusion is drawn about the optimal choice of the number of heating zones, frequencies of inductors and heating modes.

Machine-building enterprises widely use metals induction heating devices in forge-and-press and rolling production. The physical processes of heating steel blanks by high-frequency currents are accompanied by significant heterogeneity of heat generation in the blank volume and, as a result, lead to a significant non-uniformity in the distribution of the heating temperature over the blank cross section and its length. The mechanical resource of high-performance forging, stamping and rolling equipment largely depends on the temperature difference of the metal heating from optimal for large deformation during rolling and pressing of blanks, which determines high demands on the quality of metal heating at a given performance of heating installations.

Current trends in the development of induction heating installations consist in increasing the controllability of the heating process, increasing energy efficiency and reducing specific energy consumption when heating a metal with a given accuracy and performance, in improving the technological parameters of installations associated with a decrease in specific mass and dimensions, and the ability to quickly reconfigure to different blanks assortment, high repair performance and ease of maintenance [1, 2].

These requirements are achieved by creating multi-zone heating systems for steel billets with independent control of the active power and current frequency of the inductors in each heating zone. Autonomous control of the power parameters of the inductors is provided by semiconductor converters generating currents of a given frequency for each inductor. The authors propose using a multi-energy channel frequency converter as a power source, consisting of a common DC converter and a cascade multi-energy channel inverter, each cell of which is assembled according to the scheme

[3] i.e.lopatin@urfu.ru

of an asymmetric current inverter [3]. Compared with individual converters for powering the inductors of each heater zone, the proposed converter can reduce the mass-dimensional characteristics of the power source by about 30% and place it in the heating installation directly under the inductors. Structurally, the induction heating installation is constructed according to the required number of inductor-inverter modules that form controlled heating zones with independent excitation at the resonant frequency of the load oscillating circuit.

Figure 1 shows a functional diagram of a multi-zone heater.

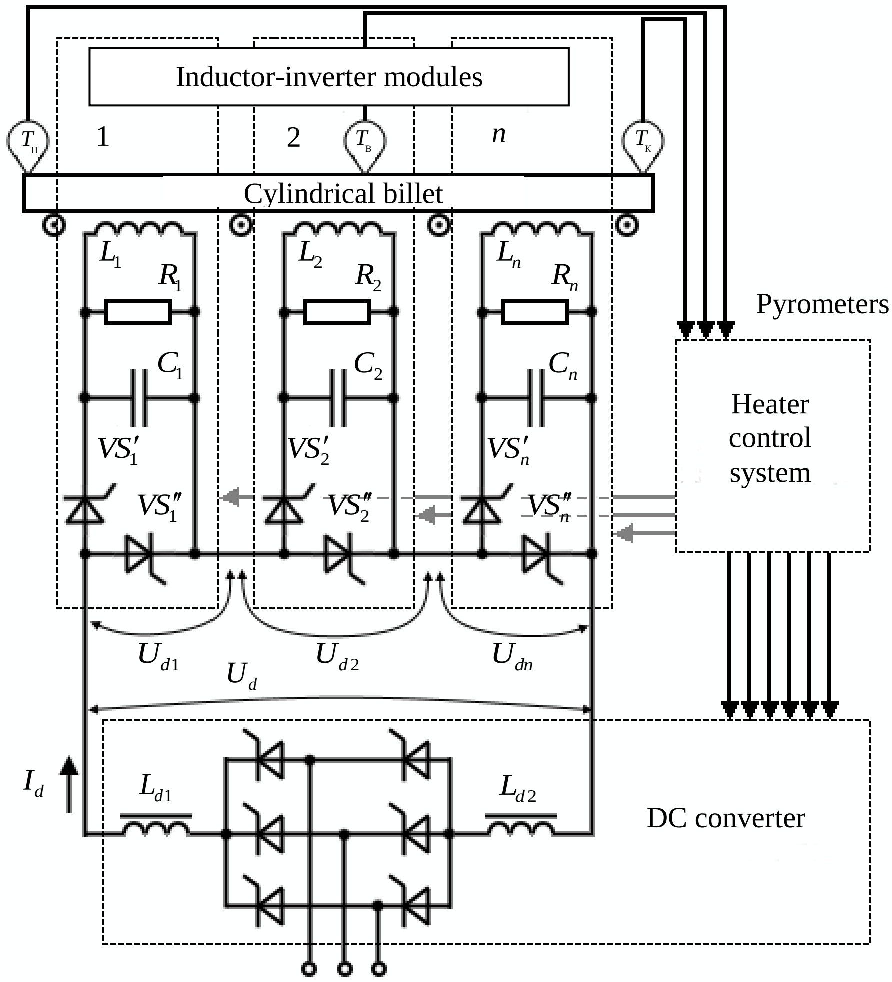


Figure 1. Functional diagram of a multi-zone heater.

Dividing the induction unit into several heating zones with an individual setting of the power and frequency of the current allows you to create the necessary power distribution profile for the heating zones and set the desired profile for the heating temperature distribution of the billets. Studies show that the process of heating blanks can be optimized according to the criterion of the heating greatest accuracy and the minimum temperature difference over the blank cross section for a given installation performance. In addition, the profile of the frequency distribution of the generated current in the heating zones can be optimized by the criterion of the highest electrical efficiency and the energy-efficient mode of operation of the installation can be determined. In multi-zone heating installations, it is possible to control the heating of the blanks under possible disturbing influences, such as a change in the speed of movement of the billets, deviation of the initial temperature of the billets, switching to another diameter of the billets, etc. By controlling the power distribution profile using temperature feedback in a certain zone of the heater (sighting point), automatic stabilization of heating and flexible adjustment to the requirements of the technological process of rolling and stamping of products is provided.

The total active power of the cascade current inverter at the input can be determined as the sum of the active powers at the input of the inverter cascades

$$P_d = I_d U_d = \sum_{i=1}^{n} P_{di}; \quad P_{di} = \frac{U_{di}^2}{R_{di}}; \quad U_{di} = \sum_{i=1}^{n} U_{di},$$

where I_d, U_d – average values of current and voltage at the output of the DC converter;

U_{di} – average voltage at the inverter inputs;

P_{di} – active power at the inverter inputs;

R_{di} – active resistance of inductors reduced to the input terminals of DC inverters.

Assuming the voltage at the inverter outputs to be sinusoidal, their value is determined depending on the setting of the oscillatory load circuits

$$U_{\text{н}i} = \frac{U_{di}}{0,45\cos\varphi_{\text{н}i}},$$

where $\varphi_{\text{н}i}$ – the phase shift angels of the main harmonics of the current and voltage at the inverter output.

The output current of the inverters has the shape of rectangular unipolar pulses with an amplitude equal to I_d. The fundamental harmonic of the output current of inverters can be determined as a result of rectangular current expansion in a Fourier series with a frequency f_i

$$I_i = 0,45 I_d.$$

The active power at the inverter output is determined by the main harmonics of the output currents and voltages and their phase shifts

$$P_{\text{н}i} = I_i U_{\text{н}i} \cos\varphi_{\text{н}i}.$$

Based on the equalities of power at the output and input of the inverters without taking into account losses in their elements, we determine the magnitude of the reduced load resistance to the DC terminals of the inverters

$$R_{di} = 0,2 R_i \cos^2\varphi_{\text{н}i}.$$

The total resistance in the converter DC circuit is determined by the sum of the inverters reduced resistances

$$R_d = \sum_{i=1}^{n} R_{di}.$$

For a given average voltage U_d at the output of the DC converter, we determine the total value of the average current I_d and the input parameters of the inverters:

$$I_d = \frac{U_d}{R_d}, \quad U_{di} = I_d R_{di} = \frac{U_d}{R_d} \cdot 0,2 R_i \cos^2\varphi_{\text{н}i}, \quad P_{di} = P_{\text{н}i} = I_{di} U_{di} = 0,2 R_i \left(\frac{U_d \cos\varphi_{\text{н}i}}{R_d} \right)^2.$$

Thus, the profile of the active power distribution over the heater inductors can be adjusted by regulating the angles of the phase shift of the main harmonics of the current and voltage at the output of the inverters

$$\varphi_{\text{н}i} = \operatorname{arctg}\left(Q_i \left(q_i - \frac{1}{q_i} \right) \right),$$

where $Q_i = \dfrac{R_i}{\sqrt{L_i / C_i}}$ – quality factor of load circuits;

L_i, C_i, R_i – inductance, capacitance and resistance of load circuits;

$\omega_{0i} = 1/\sqrt{L_i C_i}$ – natural circular frequency of load circuits;

$\omega_i = 2\pi f_i$ – working circular frequency of inverters;

$q_i = \omega_i/\omega_{0i}$ – the coefficients of the detuning of the operating frequency of the inverter from the resonant frequency of the load circuits.

Inverters are controlled by supplying control pulses to thyristors with a certain frequency f_i, which is determined by the resonant frequency of the corresponding load circuit. To ensure the switching stability of the thyristor inverters, a prerequisite is a mode of operation with a capacitive response of the load circuits with a ratio of the operating frequency and the resonant frequency of the load circuit $f_i/f_{0i} > 1\,(q_i > 1)$. This condition corresponds to the mode of control pulses supply to the thyristors of inverters with lead angles β_i with respect to the voltage of the load circuits $U_{\text{н}i}$, at which the time intervals for applying the reverse voltage to the thyristors is longer than their turn-off time t_q

$$\beta_i \geq \omega_i t_q.$$

If fully controlled semiconductor devices (transistors, lockable thyristors) are used as electronic keys in inverters, the switching conditions are satisfied at $\beta_i \geq 0$, and their range of variation is significantly expanded, therefore, the range of power control in the heating zones increases because $\beta_i \approx \varphi_{\text{н}i}$.

The mathematical model of a cascade current inverter described above can be used to develop a general model for calculating the heating processes of billets in a multi-zone multi-frequency induction heating installation.

By the requirements for heating installations of forging blanks for the Kama Automobile Plant the parameters that they must provide are determined: uniform heating of cylindrical billets with diameter of 90÷130 mm; maximum outlet temperature $T_{\text{к}}$ = 1250°C; permissible range of temperature deviation over the cross section and along the length $\Delta T = \pm 25$°C; rated performance P_r = 3,8 t/h; maximum performance P_m= 4,2 t/h.

When dividing the induction heater into heating zones, it is advisable to limit their number to three, which corresponds to different physical conditions of steel billets, namely: in the first inductor, the billets have ferromagnetic properties; in the second inductor, the heating temperature reaches and exceeds the temperature of magnetic transformations, and in the third inductor, the billets are in a non-magnetic state. The electrical parameters of the inductors of each heating zone are also significantly different, therefore, to control the heating modes, independent control of the inverters is required to control the power parameters of the inductors in terms of power, voltage, frequency of the supply current.

Calculation of the heating process of the workpieces is advisable to carry out by methods based on the calculation of electromagnetic and temperature fields, providing a sufficiently high accuracy. Universal2D software package allows you to perform these calculations by the finite element method [4]. Joint calculations using mathematical models of a heater and a continuous converter at each time discretization step in the heat problem after calculating the equivalent inductances L_i and resistances R_i for a known value of C_i, using the specially developed search algorithm, the eigenfrequencies ω_{0i} of the load circuits and the operating frequencies of the inverters ω_i.

For three-zone heating of cylindrical billets with a diameter of 130 mm with a rated performance P_r=3.8 t/h, the calculation of heating modes at a constant current frequency $f_1 = f_2 = f_3$ = 1000 Hz was performed, with different profiles of relative powers in the heater zones P_1-P_2-P_3%. Heating modes can be conditionally divided into three groups:

- quick heat A-60-30-10%;
- medium heat AB1-50-40-10%, AB2-45-45-10%;
- smooth heating B1-40-40-20%, B2-40-30-30%, B3-33-33-33%.

Each profile can be characterized by a power profile coefficient

$$K_p = \frac{\Delta P_1 + \Delta P_2}{P_н},$$

where $\Delta P_1 = P_1 - P_2$; $\Delta P_2 = P_2 - P_3$; $P_н = P_1 + P_2 + P_3$.

Figure 2,a shows graphs of the billets heating temperature distribution over the zones of the heater. At the outlet of the heater, the billets surface temperature reaches $T_к = 1250$°C.

The heating temperature of the billets at the output of the first inductor at different heating modes is different. In the second inductor, the heating temperature of the workpieces reaches values higher than the temperature of magnetic transformations $T_{mt} = 750$ °C; the temperature in the third inductor is much higher than T_{mt}.

Billet heating modes significantly affect the nature of the heating temperature distribution over the cross section at the outlet of the third heater inductor. Figure 2,b shows graphs of the billets heating temperature distribution over the cross section for different heating modes, by which it is possible to determine the maximum temperature difference ΔT_m. Table 1 shows these values for various modes of heating the billets.

Table 1. Characteristics of heating modes at $f_1 = f_2 = f_3 = 1000$ Hz.

Heating mode	P_1-P_2-P_3%	$K_p = \frac{\Delta P_1 + \Delta P_2}{P_н}$	ΔT_m, °C	$W, \frac{kW \cdot h}{t}$
A	60-30-10	0,5	18,95	300
AB1	50-40-10	0,4	19,05	293
AB2	45-45-10	0,35	19,42	291
B1	40-40-20	0,2	46,55	276
B2	40-30-30	0,1	90,61	269
B3	33-33-33	0	102,91	260

In addition, table 1 shows the values of specific energy consumption for different heating modes, which is determined by the ratio of the total active power of inverters and performance W = P$_i$ / P.

Figure 3 shows the dependences ΔT_m and W on the power distribution coefficient K_p, from which it can be seen that the most effective should be considered the average heating modes AB at $K_p = 0.3 \div 0.4$, where a small temperature difference over the workpiece cross section ΔT_m and average W is achieved.

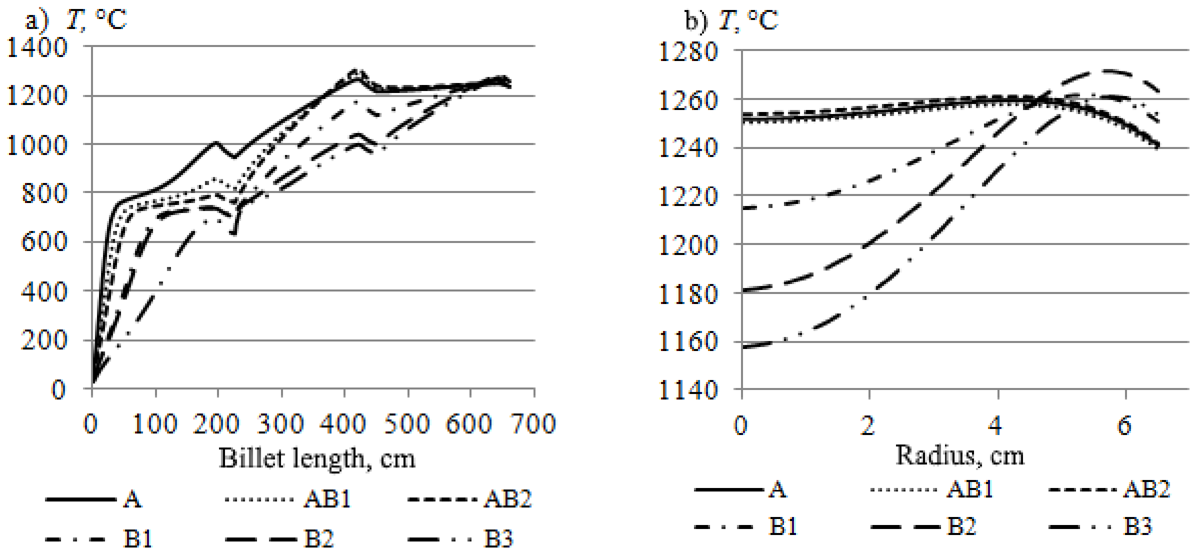


Figure 2. Distribution of the billets heating temperature along the length (a) and radius (b) for different modes at a current frequency in the inductors $f_1 = f_2 = f_3 = 1000$ Hz.

IOP Conf. Series: Materials Science and Engineering **950** (2020) 012009 doi:10.1088/1757-899X/950/1/012009

In the mode of fast heating of workpieces at $K_p = 0.4 \div 0.5$, small ΔT_{m} are provided, but W have increased values. In this mode, intense scale formation and welding of billets among themselves is observed.

In the mode of smooth heating at $K_p = 0 \div 0.3$, the characteristic ΔT_{m} has a large slope and the temperature drops along the billet cross section take unacceptably large values, while W reaches the smallest value

Based on the requirements for heating accuracy, energy efficiency, manufacturability, it is advisable to accept the modes of the average billet heating rate, where the most effective modes are AB1 and AB2.

The accuracy of heating the workpieces and energy efficiency depend on the choice of the current's operating frequency in the inductors. When heating steel billets, a rational choice of frequency can be made according to the criterion of maximum energy efficiency and efficiency of single-frequency heating of cylindrical billets [1]

$$f = \frac{6}{D^2} = 355 \div 740\ \mathrm{Hz}.$$

According to the mathematical model of the installation, the calculations of the process of heating billets with a diameter of 130 mm at the same current frequency in the inductors in the power distribution mode AB1 are made. Figure 4 shows the dependences of the maximum temperature difference ΔT_{m}, the efficiency of the inductors η_1, η_2, η_3, and the specific energy consumption W as a function of the current frequency in the inductors. As the frequency increases, ΔT_{m} decreases and reaches its minimum value at $f = 1200 \div 1400$ Hz, the specific energy consumption W also decreases to the lowest value at a frequency $f = 1200$ Hz.

The efficiency curve of the first inductor η_1 has a weakly expressed maximum corresponding to the current frequency $f_1 = 500 \div 600$ Hz. The efficiency graphs of the second and third inducers η_2, η_3 do not have a maximum and increase monotonically with increasing frequency, while their growth rate decreases at $f > 1200$ Hz. It should be noted that η_2 and η_3 differ little in value at the same frequency from each other; therefore, it is advisable to choose the optimal current frequency of the second and third heating zones according to the energy efficiency criterion in the range $f_2 = f_3 > 1200$ Hz.

When heating billets of different frequencies, it is advisable to choose the optimal current frequency according to the criterion of the highest efficiency of the inductors in the heating zone and the lowest specific energy consumption W with a minimum temperature difference over the billet cross section ΔT_{m} at the heater outlet.

Figure 5 shows graphs of the temperature difference over the ΔT_{m} section and the specific energy consumption W as a function of the frequency coefficient in the heater zones $K_f = f_2 / f_1$. As K_f increases, the temperature difference ΔT_{m} drops to a minimum value in the range $K_f = 2 \div 3$, which also corresponds to the lowest value of specific electric energy consumption W. If the optimal current frequency in the first inductor is taken to be $f = 500$ Hz, then the optimal frequencies in the second and third inductors are advisable to take $f_2 = f_3 = 1000 \div 1500$ Hz.

In the technological process of pressing products, it is often required to control the rate of delivery of heated billets, which corresponds to a change in productivity and, consequently, an increase or decrease in the speed of pushing billets through heater inductors. In this case, the accuracy of heating the billets must meet the requirements for heating quality.

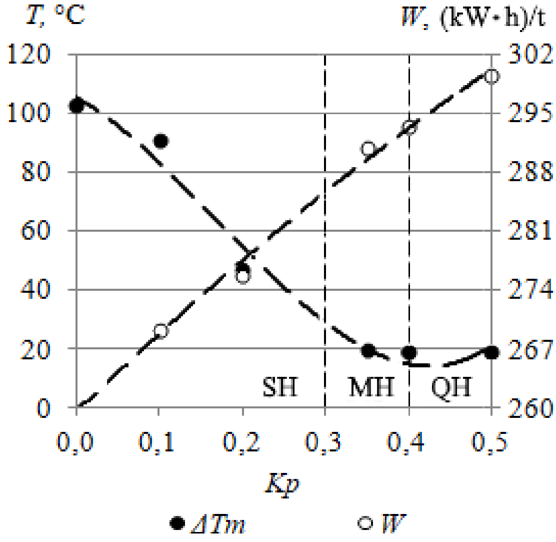


Figure 3. Dependences of the temperature difference over the cross section of the workpieces ΔT_m and specific energy consumption W on the power profile coefficient K_p;

SH – smooth heating, MH – medium heat, QH – quick heat.

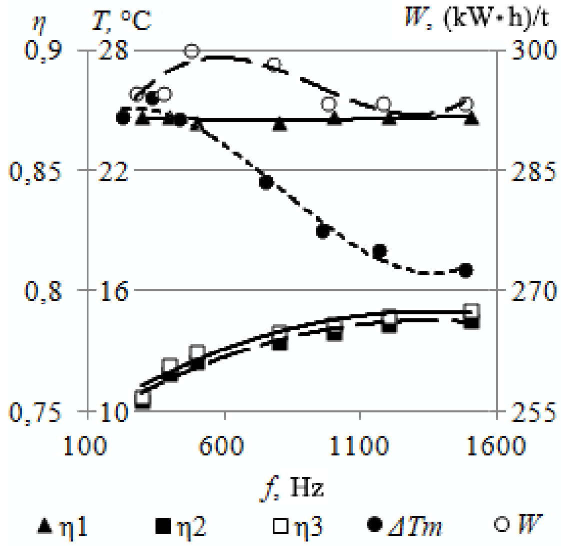


Figure 4. Frequency characteristics of the temperature difference over the cross section of the workpiece ΔT_m, the efficiency of the inductors η_1, η_2, η_3 and specific electricity consumption W.

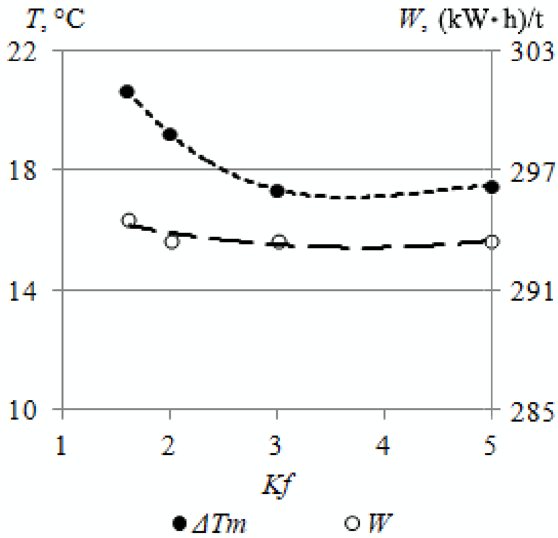


Figure 5. Characteristics ΔT_m and W as a function of the frequency multiplicity of the inductor current in heating zones.

In the three-zone heating installation under consideration, it is possible to control the heating by a controlled change in the relative power profile in the heater zones, which allows you to create a control system using temperature feedback in a certain heating zone. If power control is carried out in the middle zone of the heater when the movement speed of the workpieces changes, then the sighting zone will be inside the second inductor [5]. The position of the point of sight can be set when calculating the heating of billets with different capacities.

Figure 5 shows graphs of the billets heating temperature distribution for different capacities, which correspond to the profiles of relative power in the heater zones, shown in Table 2.

Table 2. Characteristics of operating modes for different capacities.

P, t/h	P_r, kW	P_1-P_2-P_3, %	K_p	ΔT_m, °C	$W, \dfrac{\text{kW}\cdot\text{h}}{\text{t}}$
3,4	1027	55-35-10	0,45	21,5	301
3,8	1118	50-30-10	0,40	19,4	295
4,2	1221	46-45-9	0,37	18,3	291

Since power regulation is carried out in the second heating zone when the installation performance changes, and the powers in the first and third zones remain unchanged, the relative power profile in the heater zones changes, which leads to a slight change in the temperature difference over the billet cross section ΔT_m and specific electric energy consumption W.

Figure 6 shows graphs of the billets heating temperature distribution along the length of the heater for different plant performances in the heating mode AB1 and K_f = 2, which have a point of intersection in the zone of the second inductor at a distance $2/3\ell$ from the beginning of the inductor. When a pyrometric temperature sensor is placed at this point, continuous monitoring of the billets heating mode and automatic control of the power distribution profile across the inductors can be carried out when the workpiece speed changes, which allows to stabilize the heating temperature and flexibly adapt to the conditions of the product pressing process.

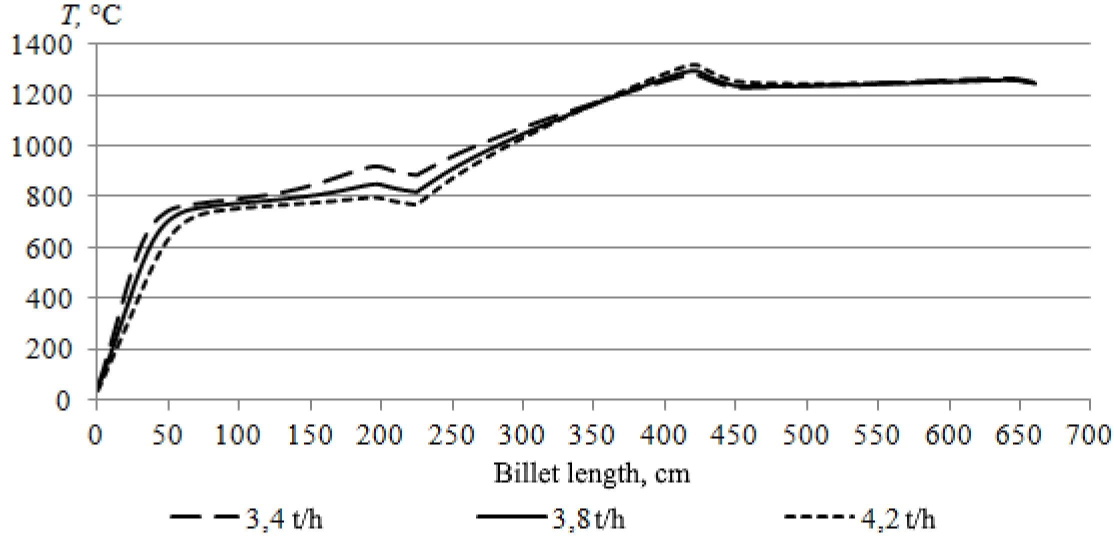


Figure 6. Billets heating temperature distribution along the length of the heater for different plant performances.

According to the results of the calculations, it is possible to determine the optimal power distribution profile for the heating zones, which corresponds to K_p = 0.34, and the optimal ratio of the current frequencies of the inductors of the first zone and subsequent heating zones, $K_f = f_2/f_1$ = 2, and the current frequency of the latter is assumed to be the same. Based on these relations, the division of the installation into three heating zones should be considered as rational, and the frequency converter can be made dual-channel with two inverters operating independently of each other and regulating the power and frequency of the current in the first inductor, as well as the power and frequency of the current in the inductors of the second and a third heating zone connected in parallel. Figure 7 shows a functional diagram of a three-zone dual-frequency heating installation with a dual-energy frequency converter.

In this case, the converter circuit is simplified, the load of the inverters is leveled, its mass-dimensional and cost indicators are reduced.

IOP Conf. Series: Materials Science and Engineering **950** (2020) 012009 doi:10.1088/1757-899X/950/1/012009

The parallel connection of inductors with the same parameters in the second and third heating zones implies their operation at the same voltage and equal current frequencies. Since when choosing AB heating mode, the workpieces in these zones are in a non-magnetic state, the active powers of the second and third inductors will be approximately the same (P_2 = P_3). Thus, the power distribution control in this installation is determined by the ratio of power in the first zone and the sum of the capacities in the second and third zones, and the coefficient of the power distribution profile is

$$K_p = \frac{(P_1 - P_2) - (P_2 - P_3)}{P_1 + P_2 + P_3} \approx \frac{P_1 - P_2}{P_1 + P_2 + P_3}.$$

Figure 8 shows graphs of the temperature difference over the billet cross section ΔT_m and specific electricity consumption W in the function K_p when heating billets with a diameter of 130 mm at a current frequency f_1 = 600 Hz and f_2 = 1200 Hz (K_f = 2), which show that the smallest ΔT_m is achieved at K_p = 0.34, while W depends little on K_p. Therefore, a rational choice of power distribution over heating zones corresponds to P_1-P_2-P_3% = 56-22-22%.

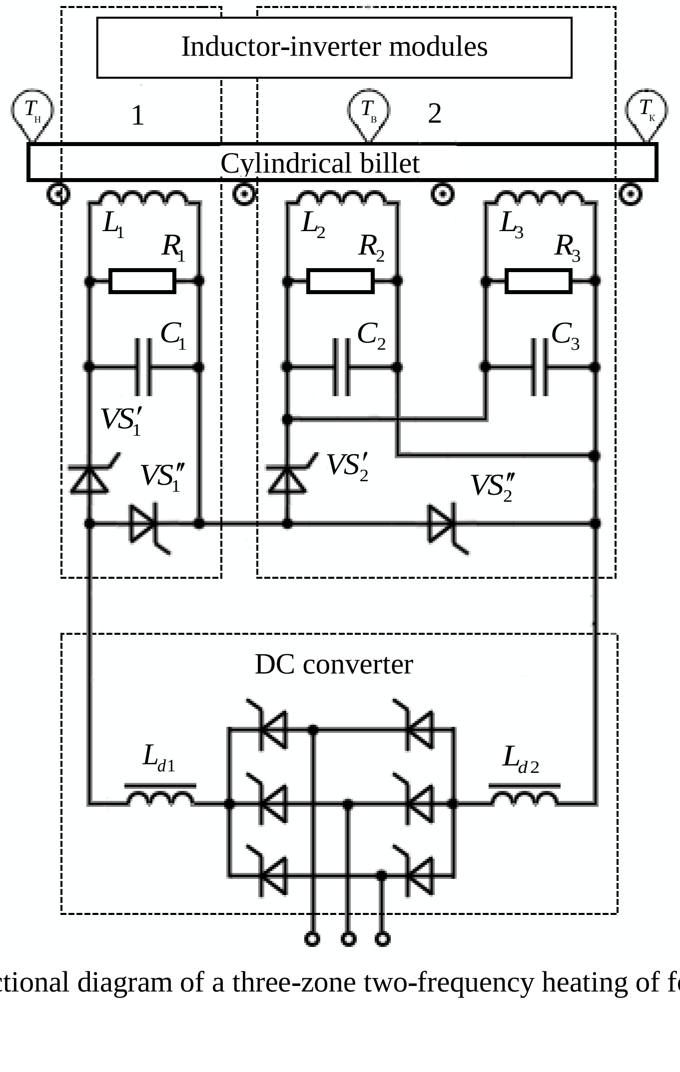


Figure 7. Functional diagram of a three-zone two-frequency heating of forging blanks.

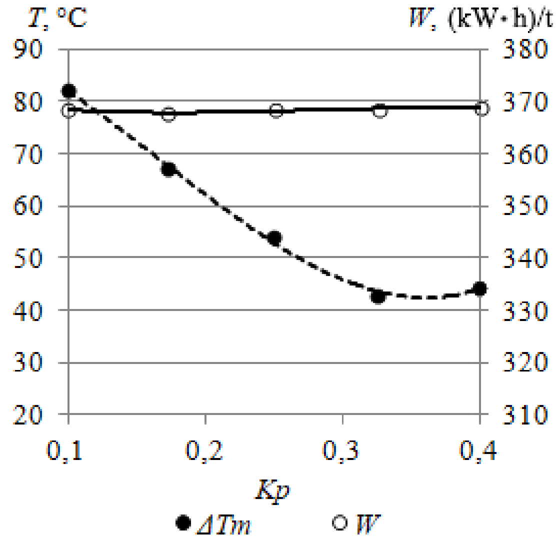


Figure 8. Characteristics ΔT_m and W from K_p for three-zone dual-frequency heating.

Thus, the method of three-zone two-frequency heating of billets makes it possible to make the optimal choice of the inductors parameters when creating induction heating plants with minimal weight and size indicators and wide functional capabilities.

The enterprises of OOO NPP «RELTEK» (Ekaterinburg) and Roboterm (Czech Republic) have developed multi-zone heating of forging blanks with a diameter of 90 ÷ 130 mm with a maximum performance of 4.2 t/h and a power 1700 kW. These plants are in pilot operation in the forging and pressing industry of the Kama Automobile Plant.

References

[1] Sluhotsky A E, Ryskin S E 1974 *Inductors for induction heating* (Leningrad: Energy) p 264
[2] Sluhotsky A E, Nemkov V S, Pavlov N A, Bamuner A V 1981 *Induction heating plants: Textbook for universities* ed A E Sluhotsky (Leningrad:. Energoatomizdat, Leningrad Department) p 328
[3] Luzgin V I, Petrov A Yu, Chernykh I V et al. 2010 *Converter device for induction heating and its variants* (Rus patent No. 2394400, Bull. Number 19)
[4] Demidovich V B, Chmilenko F V 2013 *Computer simulation of induction heating devices* (St. Petersburg: Publishing House of St. Petersburg Electrotechnical University "LETI") p 160
[5] Demidovich V B, Olenin V A, Grigoryev E A, Sitko P A 2013 Modular induction installations in forge production *Induction heating* Issue No. **4** (**26**) pp 9-12