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The influence of the supply mains parameters on the stability of phase control during resistance welding

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Abstract: Resistance welding in large-scale manufacturing is carried out with a significant number of disturbances, the cumulative effect of which may exceed the capabilities of modern control equipment. Most resistance welding control systems used in industry to compensate for existing disturbances provide welding current phase control depending on the measured parameters characterizing the process of welded joint formation. The efficiency of such controllers is largely determined by the accuracy of measuring and setting the phase control parameters, which include the opening and conduction angles of welding thyristors. The paper shows that when switching on a contact machine, a phase shift of the mains voltage occurs in the load mode relative to the mains voltage in the idle mode. Using a simplified electric equivalent circuit of a contact welding machine, the paper describes the nature of the phase shift of the mains voltage. Circuit active resistance and inductance are selected as parasitic parameters of the mains. The authors simulated the electrical processes in the contact machine according to the three-loop equivalent circuit. The study shows the influence of mains parasitic parameters on the phase regulation stability, the features of the obtained current and voltage oscillograms. Depending on the mains and contact welding machine parameters, the phase shift magnitude ranges from fractions to units of an electrical degree. With welding current parametric stabilization by the mains voltage, the influence of mains parasitic parameters can be neglected. When the regulator operates in the mode of maintaining the secondary current numerical value, a decrease in the generated current relative to the specified one is observed. The authors proposed and tested a technique for determining the parasitic parameters of the supply mains based on the results of a short circuit test.

Keywords: supply mains parameters; phase control during resistance welding; resistance welding; resistance welding control under disturbances; resistance welding diagnostics; simulation of electric processes; phase control; welding current measurement and control.

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INTRODUCTION

The leading position of resistance welding, when manufacturing sheet parts in mass production is explained by high technical and economic performance. As well as a significant amount of accumulated positive experience, in the field of application and expansion of the technology options of this method. Every year, about 100,000 resistance-welding machines are put into operation in the world for a total amount of about 1.5 billion US dollars, which is 30 % of the welding equipment market. The growing needs of the global industry allow predicting an increase in sales of resistance-welding equipment up to 2 billion US dollars by 2025 [1; 2]. In the Russian Federation, 40 % of resistance-welding equipment has a service life of more than 20 years; updating the stock of welding machines is hindered by an increase in the purchase price for equipment and components, insufficient funding for research and development in the field of welding [3; 4].

In the current economic conditions, the task of improving the quality of welding work, and expanding technology options, should be solved by the several-fold increase in the efficiency of using the equipment already available at the enterprise, without significant costs for its replacement and total redesign. In this case, a significant role is assigned to control systems and techniques of operational diagnostics of the welding equipment state [5; 6].

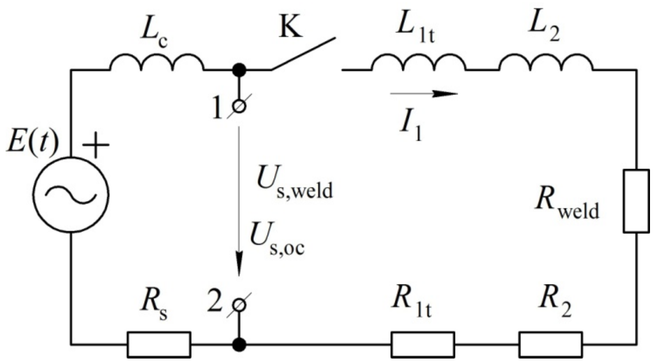
The concept of welding process control, accepted by most equipment manufacturers, considers the resistance-welding controller as an independent product implementing the preprogrammed control algorithm [7]. A significant quality improvement of the joints, was achieved through the stabilisation and correction of welding modes, implemented by modern equipment. In this area, such well-known manufacturers of resistance-welding equipment as CJSC Elektrik-MIKS (Russia), Selma (Russia), Bosch Rexroth (Germany), ENTRON Controls (USA), Welding Technology Corporation (USA), Spotron (Japan), Dengensha (Japan), and Tecna (Italy) are developing. The operation of resistance welding machines, in mass production is characterised by a number of disturbances (intensive wear of welding electrodes, compression drive, current-carrying elements, supply network instability). The cumulative effect of which cannot be compensated by modern control systems [8–10]. The issue, of increasing the stability of the resistance welding quality under various disturbances, can be solved by a comprehensive solution of the problems of operational diagnostics of the state of welding equipment, and power supply network. Simulation of electrical processes in the "machine – part" system, searching for feedback parameters, and synthesizing diagnostic and control algorithms [11–13].

In the phase control systems with effective current stabilisation based on negative feedback, the error reduction relative to the set value is achieved by introducing an integrating component into the control law. This provides effective compensation for fluctuations in the operating network voltage relative to the nominal one [14; 15]. The low quality of the supply networks, and their congestion with other consumers distorts the shape of the mains voltage signal. In this case, an error occurs in measuring and setting the time parameters of the supply voltage and current, which reduces the efficiency of phase control, and disrupts the normal operation of resistance welding controllers. The issue of resistance welding diagnostics and control, taking into account the distortion of the mains voltage shape, is not covered in the scientific literature.

The purpose of this study is to increase the reliability of diagnostics and the efficiency of resistance welding control systems, under the conditions of mains voltage fluctuations by simulating electrical processes in the "machine – part" system, and developing the techniques for diagnosing the state of supply networks.

METHODS

Preliminary calculation of the resistance welding electrical parameters, and construction of current and voltage oscillograms were performed using a simplified equivalent circuit shown in Fig. 1 a. The circuit includes series-connected active resistances of the welding transformer primary winding R_{1t}, the secondary circuit R_2, and the load R_{weld}, as well as the secondary circuit inductance L_2 and the transformer primary winding R_{1t}. The operation of the thyristor contactor is simulated by the K key position. The supply network is modelled by an ideal voltage source $E(t)$ of a sinusoidal shape and parasitic resistance R_s and network inductance L_s connected in series with it. At the terminals "1" and "2", the reference voltage U_s is measured equal to $U_{s,oc}$ at idle and $U_{s,weld}$ in the welding mode. When the machine is running in idle mode, a deviation of the mains voltage $U_{s,oc}$ relative to the nominal mains



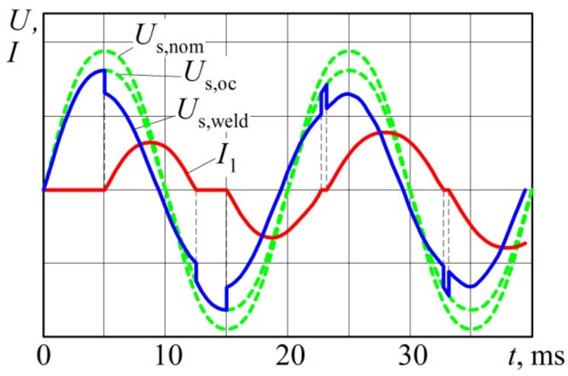


Fig. 1. *A simplified electric equivalent circuit of the contact welding machine when connecting to a non-ideal circuit (**a**) and oscillograms of the current and voltage (**b**). E(t) – ideal sinusoidal voltage source;*
R_s and L_c – active resistance and inductance of the supply mains;
R_{1m} and L_{1m} – active resistance and inductance of the transformer primary winding;
R_2 and L_2 – active resistance and inductance of the secondary circuit;
R_{weld} – active load resistance (of welded parts);
$U_{s,nom}$, $U_{s,oc}$ and $U_{s,weld}$ – mains voltage is nominal, idle, and under the load conditions;
I_1 – the current in the primary circuit of the contact welding machine

Рис. 1. *Упрощенная схема замещения контактной машины при подключении к неидеальной сети (**a**) и осциллограммы тока и напряжения (**b**).*
E(t) – идеальный источник напряжения синусоидальной формы;
R_s and L_c – активное сопротивление и индуктивность питающей сети;
R_{1m} и L_{1m} – активное сопротивление и индуктивность первичной обмотки трансформатора;
R_2 и L_2 – активное сопротивление и индуктивность вторичного контура;
R_{weld} – активное сопротивление нагрузки (свариваемых деталей);
$U_{s,nom}$, $U_{s,oc}$ and $U_{s,weld}$ – напряжение сети номинальное, в режиме холостого хода и в режиме нагрузки;
I_1 – ток в первичном контуре контактной машины

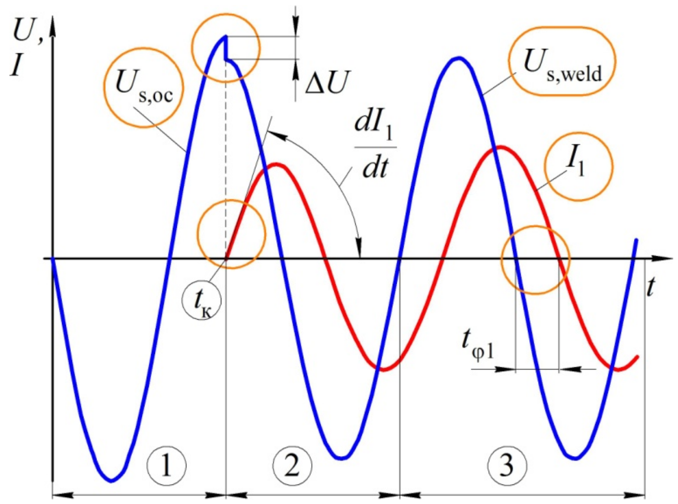


Fig. 2. *Current and voltage oscillograms at full-phase switching-on.*
$U_{s,oc}$ and $U_{s, weld}$ – mains voltage in idle mode and in load mode;
I_1 – the current in the primary circuit of the contact welding machine;
ΔU – power failure; $t_к$ – commutation moment of the thyristor contactor;
dI_1/dt – primary current growth rate; $t_{\varphi 1}$ – phase shift
Рис. 2. *Осциллограммы тока и напряжения при полнофазном включении.*
$U_{s,oc}$ and $U_{s, weld}$ – напряжение сети в режиме холостого хода и в режиме нагрузки;
I_1 – ток в первичном контуре контактной сварочной машины;
ΔU – провал напряжения; $t_к$ – момент коммутации тиристорного контактора;
dI_1/dt – скорость нарастания первичного тока; $t_{\varphi 1}$ – фазовый сдвиг

voltage $U_{s,nom}$ is observed, which is explained by the network congestion by other electric energy consumers. When the machine operates in the welding mode, an abrupt decrease in the mains voltage $U_{s,weld}$ relative to the idle voltage $U_{s,oc}$ is observed, which manifests itself both by a decrease in the voltage supplied to the contactor and by a voltage phase lag $U_{s,weld}$ relative to the voltage $U_{s,oc}$, which is shown in Fig. 1 b.

The authors proposed to calculate the parasitic parameters of the supply network (resistance R_s and inductance L_s), based on the results of a short circuit test in the full-phase switching on of the welding machine. On the oscillogram of currents and voltages, three characteristic regions can be distinguished, which are shown in Fig. 2. The first one – before switching the thyristor contactor, where the effective mains voltage in the idle mode $U_{s,oc}$ is measured. The second – after switching the thyristor contactor, when the transient processes occur. This area lasts 2…3 half cycles of mains voltage. At the switching moment t_k of the thyristor contactor, the power failure ΔU and the rate of the primary current rise dI_1/dt are measured. The third area characterised by a sinusoidal form of voltage and current is used to measure the effective voltage of the network under load $U_{s,weld}$, the primary current I_1 and the current-voltage lag angle φ_1. It should be noted that the short circuit mode is characterised by the largest phase shift $t_{\varphi 1}$, which allows improving the accuracy of the calculation of parasitic network parameters. The accuracy increases as well with an increase in the primary current I_1, therefore, the maximum stage of the welding transformer was taken for measurements. The maximum suppression of transient processes when the thyristor contactor is turned on is ensured when switching at the moment of the maximum voltage $U_{s,oc}$, therefore, the first switching on of the thyristors was performed at an opening angle of α=90° el.

Since at the switching moment the current I_1 is equal to zero, the observed power failure ΔU is completely caused by the voltage drop on the parasitic inductance of the network L_s and can be calculated according to the formula (1) from the primary current growth rate dI_1/dt:

$$L_s = \frac{\Delta U}{\frac{dI_1}{dt}}. \quad (1)$$

The active resistance R_s is calculated according to the formula (2) taking into account the supply network frequency f_s:

$$R_s = \sqrt{\left(\frac{U_{s,oc}}{I_1}\right)^2 - \left(\frac{U_{s,weld}}{I_1}\sin\varphi_1 + 2\pi f_s L_s\right)^2} - \frac{U_{s,weld}}{I_1}\cos\varphi_1. \quad (2)$$

The supply network parasitic parameters were measured in the resistance welding laboratory of Togliatti State University, using an MT-4019 resistance welding machine, an RKDP-0401 welding process recorder, and an RMS-24 welding controller. The thyristor contactor was switched on at the 8th stage of the transformer.

RESULTS

The mains voltage measured at no load was $U_{s,oc}$=380 V. At the time of switching the thyristor contactor, the power failure was ΔU=39 V. The primary current growth rate was dI_1/dt=148 kA/s, the mains voltage measured in the load mode was $U_{s,weld}$=343 V, and the primary current of full-phase switching in the load mode was I_1=258 A. The lag angle of the primary current from the voltage was φ_1=61° el. When calculating according to formulas (1) and (2), the supply network parasitic parameters R_s=0.14 Ohm and L_s=0.26 mH were obtained.

Simulation of electrical processes in welding equipment, taking into account the network parasitic parameters R_s and L_s, was performed using a T-equivalent circuit and bringing the parameters to the transformer primary winding [16]. The supply network is modelled by an ideal sinusoidal voltage source E. The on state of the thyristor contactor is modelled by a jumper strap; the calculated equivalent circuit in this case is shown in Fig. 3 a. The off state of the thyristor contactor is modelled by an electrical circuit break; the calculated equivalent circuit in this case is shown in Fig. 3 b. The scheme additionally takes into account the transformer core parameters R_0 and L_0. The mathematical description of electrical processes was performed using the state-variable approach; the inductance currents $L_{1t}+L_s$ (I_1 current), inductance L_2 (I_2 current), and inductance L_0 (I_0 current) were chosen as state variables. The following systems of differential equations of the first order for the on (3) and off (4) thyristor contactor states are obtained:

$$\frac{d}{dt}\begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} = \begin{bmatrix} -\frac{R_0+R_s+R_{1t}}{L_s+L_{1t}} & \frac{R_0}{L_s+L_{1t}} & \frac{R_0}{L_s+L_{1t}} \\ \frac{R_0}{L_2} & -\frac{R_0+R_2+R_{weld}}{L_2} & -\frac{R_0}{L_2} \\ \frac{R_0}{L_0(I_0)} & -\frac{R_0}{L_0(I_0)} & -\frac{R_0}{L_0(I_0)} \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s+L_{1t}} \\ 0 \\ 0 \end{bmatrix} E(t) \quad (3)$$

$$\frac{d}{dt}\begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\frac{R_0+R_2+R_{weld}}{L_2} & -\frac{R_0}{L_2} \\ 0 & -\frac{R_0}{L_0(I_0)} & -\frac{R_0}{L_0(I_0)} \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix}. \quad (4)$$

Using (3) and (4), the transient process was calculated when the MT-4019 machine was turned on at the thyristor opening angle of α=60° el. for previously found network parasitic parameters R_s=0.14 Ohm, L_s=0.26 mH. The calculated current and voltage curves shown in Fig. 4, have characteristic failures, at the moment of switching of the thyristor contactor, the shape and size of which correspond to the oscillograms obtained using the RKD-0401 recorder. Fig. 4 shows as well, that the zero crossing point of the mains voltage in the idle mode $U_{s,oc}$ does not coincide with the zero-crossing point of the mains voltage in the welding mode $U_{s,weld}$, while the actual opening angle of the thyristors α differs from the specified α_{set}.

DISCUSSION

The analysis of the results of full-scale experiments and mathematical modelling shows that under the conditions of mass production, the supply network imperfection leads to a disruption in the normal course of phase control during resistance welding. The correct setting of the thyristor opening angle α, measured from the zero-crossing point of the idle mains voltage $U_{s,oc}$ is possible only in the first half-cycle of the welding current. On subsequent half-cycles, the $U_{s,oc}$ idle voltage signal is absent. Instead, there is a phase-shifted $U_{s,weld}$ voltage signal in the welding mode. Under the conditions of non-ideal supply network, the actual thyristor opening angle α differs from the α_{set} value, specified by the regulator by the allowance value Δα:

$$\alpha = \alpha_{set} - \Delta\alpha . \quad (5)$$

The allowance value is calculated according to (3)–(5) for predetermined supply network parasitic parameters, and can be represented by a family of curves depending on the actual thyristor, opening angle α, power factor cosφ,

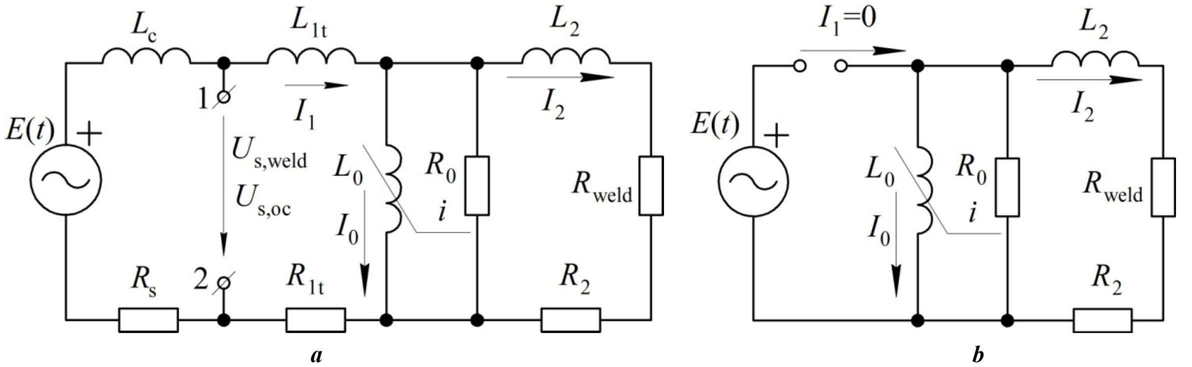


Fig. 3. *Calculated equivalent circuit of the contact welding machine with on (**a**) and off (**b**) thyristor contactor*
Рис. 3. *Расчетная схема замещения контактной сварочной машины при включенном (**a**) и выключенном (**b**) тиристорном контакторе*

and machine load Q, as shown in Fig. 5. Depending on the parameters of the welding mode and phase control, the allowance $\Delta\alpha$ ranges from tenths to units of an electrical degree. It grows with a decrease in the power factor (cosφ), and the phase regulation depth (angle α), an increase in the load Q of the welding machine in terms of power.

When using welding regulators that implement parametric stabilisation of the welding current to the mains voltage (RKM-803 and RKM-804 in the parametric stabilisation mode, RVI-801), the influence of the network parasitic parameters on the quality of welding can be neglected. Thus, for the parametric stabilisation algorithm [17] implemented in the RKM-803 and RKM-804 controllers, the actual heating level N (the ratio of the effective current to the full-phase current) differs slightly from the specified heating level N_{set}, moreover upwards, as shown in Fig. 6 a. From this, the authors can conclude that the phase shift of the observed voltage $U_{s,weld}$ relative to the idle voltage $U_{s,oc}$ does not violate the phase regulation when implementing the parametric stabilisation algorithms.

The quantitative setting and maintenance of the welding current value implemented in most modern resistance welding controllers, under the conditions of a phase shift in the welding voltage $U_{s,weld}$ relative to the idle voltage $U_{s,oc}$, can take place with significant violations. When the controller operates in the mode of maintaining the welding current numerical value, the generated current I_2 is equal to the specified current I_{set} only at two key points α_{set}' and α_{set}'', which were used when constructing the regulation characteristic. For intermediate values of the thyristor opening angle α_{set}, the generated current $I_2(\alpha_{set}-\Delta\alpha)$, which corresponds to the actual thyristor opening angle according to (5), is less than the set current I_{set}. The resulting error is shown in Fig. 6 b. Thus, for the MT-3003 and MT-1933 stationary machines, the deviation of generated and set currents during welding of 08Yu steel samples with a thickness of (1.5+1.5) mm was 1.5 and 0.5 kA, respectively.

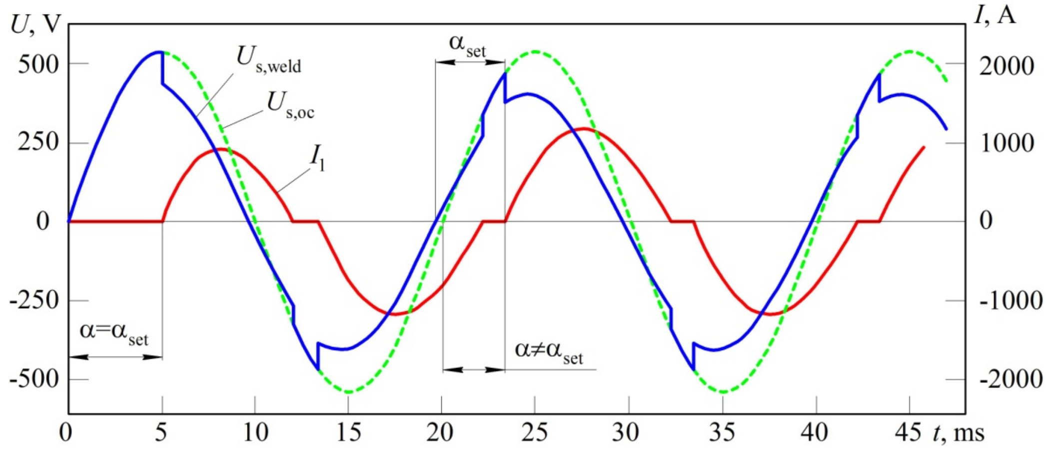


Fig. 4. *Calculated voltage and current curves built taking into account the supply mains parasitic parameters*
Рис. 4. *Расчетные кривые напряжения и тока, построенные с учетом паразитных параметров питающей сети*

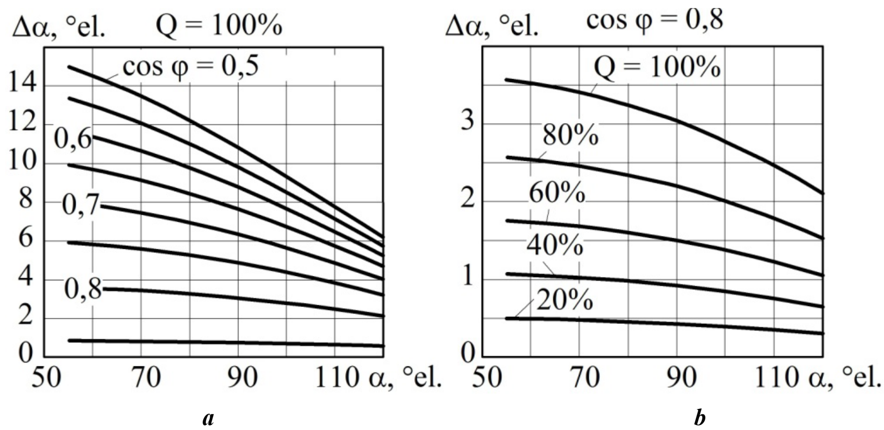


Fig. 5. *The dependence of the allowance Δα on the control angle α at different loads by power Q for cosφ=0.8 (**a**) and at 100 % load of the welding machine (**b**)*
Рис. 5. *Зависимость поправки Δα от угла регулирования α при различной загрузке по мощности Q для cosφ=0,8 (**a**) и при 100 % загрузке сварочной машины (**b**)*

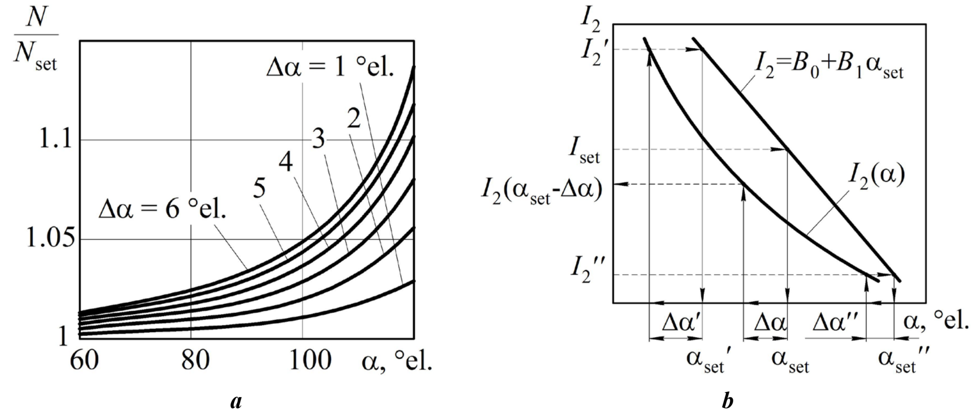


Fig. 6. *The ratio of the actual heating level N to the set heating level N_{set} with parametric stabilization at the parametric stabilization (**a**);*
*current setting error at the quantitative stabilization of welding current (**b**)*
Рис. 6. *Отношение действительного уровня нагрева N к заданному уровню нагрева N_{set} при параметрической стабилизации (**a**);*
*погрешность задания тока при количественной стабилизации сварочного тока (**b**)*

To diagnose resistance welding and predict the quality of joints, an assessment of the time intervals of the thyristor contactor operation is performed with the calculation of the power factor cosφ [18–20]. The error in setting the opening angle of thyristors Δα ranging from fractions to units of an electrical degree disrupts the normal operation of control and diagnostic algorithms. So, at Δα=1° el., the actual value of cosφ turns out to be more than calculated by 1 ... 10 %, and at Δα = 3° el., the error can reach 20 %. Reducing the phase regulation depth, and increasing the value of the power factor cosφ through optimising the welding mode parameters and the design of the resistance machine secondary circuit, can significantly reduce the influence of Δα on the accuracy of control and diagnostics of resistance welding.

CONCLUSIONS

With a phase shift of the mains voltage in the load mode relative to the mains voltage in the idle mode, an error in setting the opening angle of the thyristors occurs, which reaches several electrical degrees.

The study shows that in the case of parametric control of the current by the network voltage, the influence of network parasitic parameters can be neglected. With the secondary current numerical maintenance, the generated current turns out to be less than the specified one due to the occurrence of an error in setting the thyristor opening angle α.

A technique for calculating the supply network parasitic parameters, based on the results of a short circuit test in the full-phase switching mode is proposed.

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Влияние параметров питающей сети на стабильность фазового регулирования при контактной сварке

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Аннотация: Контактная сварка в условиях массового производства выполняется при значительном количестве возмущений, совокупное действие которых может превышать возможности современной аппаратуры управления. Большинство систем управления контактной сваркой, применяемых в промышленности для компенсации действующих возмущений, предусматривает фазовое регулирование сварочного тока в зависимости от измеренных параметров, характеризующих процесс формирования сварного соединения. Эффективность работы таких регуляторов в значительной мере определяется точностью измерения и задания параметров фазового регулирования, к которым относят углы открытия и проводимости сварочных тиристоров. В работе показано, что при включении контактной машины происходит фазовый сдвиг напряжения сети в режиме нагрузки относительно напряжения сети в режиме холостого хода. С использованием упрощенной электрической схемы замещения контактной сварочной машины в работе описана природа фазового сдвига напряжения сети. В качестве паразитных параметров сети выделены активное сопротивление и индуктивность сети. Моделирование электрических процессов в контактной машине выполнено согласно трехконтурной схеме замещения. Показано влияние паразитных параметров сети на стабильность фазового регулирования, особенности получаемых осциллограмм тока и напряжения. В зависимости от параметров сети и контактной сварочной машины, величина фазового сдвига составляет от долей до единиц электрического градуса. При параметрической стабилизации сварочного тока по напряжению сети влиянием паразитных параметров сети можно пренебречь. При работе регулятора в режиме поддержания численного значения вторичного тока наблюдается уменьшение создаваемого тока относительно заданного. Предложена и апробирована методика определения паразитных параметров питающей сети по результатам опыта короткого замыкания.

Ключевые слова: параметры питающей сети; фазовое регулирование при контактной сварке; контактная сварка; управление контактной сваркой в условиях возмущений; диагностика контактной сварки; моделирование электрических процессов; фазовое управление; измерение и регулирование сварочного тока.

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