ON THE SOLUTION OF THE PROBLEM OF SYNTHESIS OF THE CONTROL SYSTEM FOR THE PROCESS OF DOSED FEED OF ELECTRODE WIRE FOR ARC WELDING EQUIPMENT

Goal. Refinement of the methodology for the development of an effective control system for an electric drive with controlled relay-type regulators for organizing a metered feed of an electrode wire using the parameters of the arc process with the possibility of using it in design practice and practice of technological application. Methodology. The proposed method for the mathematical description (mathematical model) of the system of the developed structure electric drive - arc process with current feedback of welding with a variable structure device is based on the theory of automatic control as applied to nonlinear elements, the application of the theory of operational calculus. At the same time, a selection and description of a nonlinear node in the feedback circuit in the form of a relay element with a certain structure and subsequent linearization of this element was made. As an electric motor of the electrode wire feeder, a new development of a specialized valve electric motor is used, which is used in the system with a microprocessor controller. Results. Due to the presence of a substantially nonlinear link, the calculation of the valve electric drive system – the arc process can be found on the basis of a system of nonlinear differential equations, which is practically impossible for practical application. In this work, these complications are overcome on the basis of a rational choice of the description of the nonlinear link, its harmonic linearization and obtaining on this basis a mathematical description of the system, from which, using the methodology of operational calculus, the relations necessary for calculating the parameters of the system are determined in analytical form. Originality. The problem of calculating a rather complex problem of mathematical description of the valve electric drive system – a technological link in the form of an arc process with a substantially nonlinear link in the feedback circuit in the work is solved with the effective use of a set of methodological methods, which include as a means of representing individual links, including nonlinear links selected simplifications and solutions of the obtained differential equations using original methods of operational calculus. The proposed method (mathematical model) is tested in two directions – oscillography of a real system, as well as system simulation. Practical significance. Using the developed methods for describing the control system, it is possible to calculate its characteristics and, on their basis, select the parameters for setting the electric drive controller, which allows, without additional experimental research, to obtain the necessary characteristic of the transfer of electrode metal, and, consequently, the quality of the result of the arc process. References 12, figures 4.

Keywords: welding process, electrode wire, pulse feed, control system, mathematical description, calculation.

Introduction. Arc mechanized and automatic welding and consumable electrode surfacing is one of the most common technological processes with a wide range of applications and it is predicted that it will continue to develop in the future, improving in all directions and areas of application. The widespread use of mechanized arc welding using both solid and flux-cored electrode wires determines the search for new technical solutions aimed at improving the process technology, as well as updating the park of mechanized and automatic equipment with new technical capabilities [1].

The main directions in improving the technology of welding and surfacing and the corresponding types of equipment are associated with the use of pulse algorithms for the functioning of automatic and semi-automatic...
systems [2]. Recently, the technical and technological improvement of automatic and semi-automatic devices is associated with the development and designing of one of the main systems – an electrode wire feed system with a basic unit – a feed mechanism. The main developments in this direction are associated with the use of a pulse feed of an electrode wire. There are developments of both simple systems with practically no regulation of pulse parameters, and with sufficiently perfect mechanisms, and this is described in detail in [3]. It can be noted that the use of a modern feed mechanism providing pulse motion of the electrode wire allows, with correctly selected parameters, to control the transfer of electrode metal drops, which in turn allows (mainly) [4, 5]:

- to significantly reduce the loss of electrode metal for waste and splashing;
- to change the geometrical dimensions of the weld and weld bead, as well as the heat-affected zone;
- to influence the structure of the weld metal, improving its operational properties (strength, wear resistance, including corrosion, etc.);
- to reduce energy costs for conducting welding and surfacing processes.

Additionally, it should be noted the low value of the inertia of the electric motor.

The improvement of the electrode wire feed system is developed using the achievements of the element base and technical solutions based on them. The latest developments of mechanisms with pulse algorithms of functioning are based on the use of gearless electric drives with brushless valve and stepper motors with microprocessor control of the rotation frequency of their shafts, and, consequently, the movement of the electrode wire with high speed levels. Such systems are constantly being improved in different directions and in different systems of automatic welding and surfacing equipment. One of them develops quite intensively in the electrode wire feed system and is associated with the introduction of feedbacks into the electric drive regulator according to the parameters of the arc process – either current or voltage. This solution made it possible to implement a new type of arc process – welding-surfacing with a dosed feed of the electrode wire [6].

The goal of the work is the refinement of the methodology for the development (synthesis) of an effective control system for an electric drive with controlled relay-type regulators for organizing a dosed feed of electrode wire using the parameters of the arc process with the possibility of using it in design practice and practice of technological application.

Statement of the problem. Figure 1 schematically shows the formation of feedback on the arc process. In this case – by the welding current in the process with short circuits of the arc gap at the moments of switching on and off the drive of the electrode wire feed, depending on the desired (required) results of technological processes of welding and surfacing. Switching times on the graph in Fig. 1 marked with points «c» ($I_{w_{\text{min}}}$) and «b» ($I_{w_{\text{max}}}$).

![Fig. 1. The operation algorithm of the electrode metal transfer control system associated with the parameters of the arc process current: $I_w$ – welding current; $U_w$ – welding voltage; $v_e$ – feed speed of the electrode wire; $a$ – transition of the drop into the bath; $b$ – pause in feed rate; $c$, $d$ – start of feeding](https://ssrn.com/abstract=3824654)
the voltage of the welding process in the feedback. Conditions may exist where voltage feedback will take priority.

Feedback makes it possible to automatically self-adjust the electric drive of the feed mechanism according to the parameters corresponding to the natural (physical) nature of the welding arc and, which eliminates the time-consuming choice of frequency and duty cycle of mechanical pulses, the parameters of which are very difficult to predetermine.

Figure 2 schematically shows the system of dosed control of the arc welding process with short circuits of the arc gap, including the main links of the system with transmission elements: $W_d$ – valve motor; $W_s$ – arc welding process; $W_r$ – electric drive regulator; $W_{nl}$ – nonlinear link that determines the moments of switching the welding current at the minimum $i_{w\text{ min}}$ and maximum $i_{w\text{ max}}$ currents of the welding process.

The expressions for determining the gear ratios of the links are defined as follows.

It is known that the transfer function of a valve motor in operator form can be identified with the transfer function of a DC motor [7] and written in a somewhat simplified form

$$W_d(p) = \frac{\omega(p)}{U(p)} = \frac{K}{T_m p + 1}, \quad (1)$$

where $\omega$ is the shaft rotation frequency; $U$ is the supply voltage; $K$ is the value inversely proportional to the constructive constant of the electric motor; $T_m$ is the electromechanical constant of the phase of the electric motor, taking into account the inertial characteristics of the gearless feed mechanism (rollers).

For the transfer function of the link describing in the operator form the arc welding process with short circuits of the arc gap, an expression is proposed that we obtained in [8].

$$W_{nl}(p) = \frac{i_{nl}(p)}{\omega(p)} = \frac{E}{R_1 p + 1 + p + k}, \quad (2)$$

where

$$T_1 = \frac{L}{R + 0.5 \cdot b_1}; \quad k = \frac{A \cdot H \cdot E}{R + 0.5 \cdot b_1},$$

in turn $L$, $R$ are the inductance and equivalent resistance of the welding circuit, respectively; $b_1$ is the coefficient characterizing the slope of the static characteristics of the arc to the current axis; $E$ is the electric field strength in the arc column;

$$A = \frac{1}{M \cdot \pi \cdot r^2}; \quad H = U_i(0.285 - 0.0052 \cdot U),$$

where $U_i$ is the open circuit voltage of the welding power source; $M$ is the coefficient determining the thermal state of the electrode metal

$$M = C_n \cdot \gamma_n \cdot T_n - C_o \cdot \gamma_o \cdot T_o + r_n \cdot \gamma_o,$$

where $C_n, C_o$ is the heat capacity of the metal at melting and ambient temperatures, respectively; $\gamma_n, \gamma_o$ is the density of the metal at melting and ambient temperatures, respectively; $r_n$ is the latent heat of fusion; $T_n, T_o$ are the melting temperature of the electrode metal and the ambient temperature, respectively;

$$S = \frac{E}{R + 0.5 b_1}.$$

Usually, for an electric drive regulator providing additional control qualities (minimum overshoot, minimum possible time for changing the frequency of rotation of the electric motor shaft in transients, etc.), various structures are used, for example, PI regulators, relay current regulators, etc. In our case, to simplify consideration of the dosed control system without prejudice to the essence of the analysis, we take the regulator transfer function in the operator representation in the following form

$$W_{p}(p) = \frac{U_{p}(p)}{U(p)} = \frac{K_p}{T_p p + 1}, \quad (3)$$
where $U_{in}$ is the supply voltage; $K_p$ is the regulator gain; $T_p$ is the controller time constant.

The description of the transfer function of a nonlinear link providing switching of voltage levels proportional to the current of the welding process presents some difficulties, in particular, because the nonlinearity has an asymmetric nature.

Several options for analyzing such a nonlinear system can be proposed. The simplest and most effective option may be using mathematical modelling. However, such a solution is not always possible for use in design and especially technological practice when choosing the parameters of the nonlinear link in the feedback circuit that determine the characteristics of the transfer of electrode metal drops.

Presentation of the main material. In the system under consideration, by switching, the connections between the elements change depending on its state, therefore, such a system can be fully attributed to a system with a variable structure [9]. The structural diagram of such a system changes during the transient in such a way as to ensure the high-quality performance of control tasks for the welding process by influencing the transfer of electrode metal drops. A serious obstacle to the use of analytical methods and computational tools for the construction of effective control algorithms for modern technical objects, which include arc welding processes, including with doses feed, is a wide range of their characteristics, both in the composition of the system components and in the effects. A promising method in solving problems of describing systems with variable structure can be the use of techniques for analyzing sliding modes. However, the obvious complexity of obtaining analytical expressions for this method of studying a system with a variable structure also cannot be applied both in design and in technological practice.

The two above-mentioned methods of analyzing a system with a nonlinear element are quite accurate, but obviously difficult for application. It is necessary to consider approximate methods of obtaining the mathematical description of nonlinear links [10, 11]. A number of these methods are discussed in the monograph [12]. It seems to us that the harmonic balance method will be the most acceptable for the considered control system.

Taking into account (4)-(7), as well as using simple algebraic transformations, we obtain an approximate linear dependence of the output variable of the nonlinear link on its input variable: with the transfer function

$$W_{nl}(p) = c\left[\frac{1}{2\pi}b_m\frac{m\cdot b_m-x_0^0}{A} + \arcsin\frac{m\cdot b_m-x_0^0}{A}\right],$$

Thus, under the influence of harmonic vibrations, the nonlinear link seems to be linearized and can be considered approximately as a linear link. The coefficients $q$ and $q'$ indicated above can be called harmonic gains of the nonlinear link. It can be seen from the formulas for the coefficients that $F^0$, $q$ and $q'$ depend on the amplitude of the input signal. This dependence reflects the nonlinear properties of the link and because of it, the superposition principle is inapplicable for a harmonically linearized nonlinear link.

The transfer function of the closed-loop control system of the arc welding process with a dosed feed of the
electrode wire can be written as an equation in operator form as follows:

\[ i(p) = \frac{W_p(p) \cdot W_d(p) \cdot W_w(p)}{U_{vt}(p) + \frac{1}{1 + W_p(p) \cdot W_d(p) \cdot W_w(p) \cdot W_m(p)}}. \]  

(9)

where \( U_{vt} \) is the setting voltage.

Let us introduce the notation

\[ D = c^2 \cdot \left( \frac{1}{2} - \frac{1}{2\pi} \arcsin \frac{b_2 - x^0}{A} + \arcsin \frac{m b_2 - x^0}{A} \right) + \frac{1}{\pi A} \sqrt{\frac{b_2 - x^0}{A^2} + \left[ 1 - \frac{(m b_2 - x^0)^2}{A^2} \right]} \].

(10)

Taking into account (1)-(3), (9)-(11), we obtain a complete expression for determining the desired dependence \( i(p) \) in the operator form:

\[ i(p) \frac{1}{U_{vt}(p)} = \frac{K_{p} \cdot K_{d} \cdot S}{(T_d \cdot p + 1) \cdot (T_d \cdot p + 1) + (T_d \cdot p + k) \cdot (b_2 - x^0) + \left( m b_2 - x^0 \right) \left( T_d \cdot p + k + K_{d} \cdot S \right)} \]  

(12)

The solution of the operator equation (12) in the form of obtaining the analytical dependence \( i = f(U_{vt}) \) presents certain difficulties, including because of the high order of \( p \). Such a possibility is presented when using machine research methods and using mathematical modelling.

Modern mathematics does not allow solve equations in general form above the third order by simple methods, so we will look for ways to lower the order of the unknown \( p \) whose maximum order is \( p^3 \).

Several engineering calculation methods are used to study a linearized link system. First of all, take into account that the time constant of the regulator is very small and the transfer function of the link (3) can be excluded or included in the transfer function with the gain that is taken into account by the link (1). Taking this into account, equation (12) can be rewritten in a simplified form

\[ i(p) \frac{1}{U_{vt}(p)} = \frac{K_{d} \cdot S}{T_d \cdot T_d^2 \cdot p^3 + (T_d^2 + T_d \cdot T_d) \cdot p^2 + (T_d \cdot k + T_d \cdot T_d) \cdot p + k + K_{d} \cdot S \cdot (D - N \cdot p)} \]  

(13)

We will study the linearized equation (13) using one of the engineering methods – the frequency method of E.P. Popov.

From expression (13) we determine the characteristic equation

\[ (T_d \cdot k + T_d + T_d \cdot S \cdot N) \cdot \omega + k - T_d \cdot T_d^2 \cdot \omega^2 = 0. \]  

(16)

The frequency of the periodic process \( \omega \) is determined by solving the quadratic equation (16). The discriminant of equation (16)

\[ (T_d \cdot k + T_d + T_d \cdot S \cdot N)^2 - 4 \cdot T_d \cdot T_d^2 \cdot k = 0. \]  

(17)

An important conclusion follows from expression (17) that self-oscillations with frequency \( \omega \) can take place under the condition

\[ (T_d \cdot k + T_d + T_d \cdot S \cdot N)^2 \geq 4 \cdot T_d \cdot T_d^2 \cdot k. \]  

(18)

Having determined the frequency \( \omega \) from equation (15) and substituted it into equation (15), one can also determine the amplitude of self-oscillations.

Since, among other things, the frequency and amplitude of self-oscillations are determined by the values of \( b_2 \) and \( m b_2 \), which practically corresponds to the minimum \( I_{w, min} \) and the maximum \( I_{w, max} \) values of the current of the arc process, which in turn determines the nature of the transfer of the electrode metal, which determines the results of welding with the use of a dosed feed of the electrode wire.

**Checking the obtained results.** The evaluation and reliability of the results obtained were carried out by comparing the oscillograms of the arc process current with the results obtained in mathematical modelling with the same initial data.

Figure 4 shows several options for presenting currents and voltages for mechanized electric arc welding in a protective gas environment when feeding the electrode wire in the usual way (Fig. 4,a) and using the algorithms for dosed feed (Fig. 4,b).

Comparison of real oscillograms of current and voltage with data obtained by computer simulation using the MATLAB (Simulink) environment (Fig. 4,c) indicate a fairly close result in frequency of the transfer of electrode metal.

A coincidence was obtained within 10-15 % and this is an acceptable result for the technologies of mechanized and automatic welding processes – surfacing with pulse algorithms for feeding the electrode wire and confirming the efficiency of the proposed method.

The proposed method for calculating the operating parameters of an electric drive in the system of technical implementation of the welding and surfacing method with a dosed feed of the electrode wire based on the introduction of an adjustable feedback on the arc process current has a very important practical application and makes it possible to determine the combination of the minimum \( I_{w, min} \) and maximum \( I_{w, max} \) values of the welding process current which determine the frequency and amplitude of the arc current pulses and, as a result, the controlled frequency of transfer of the electrode metal drops and thereby provide the quality indicators of the resulting welds and deposited layers (spattering, heat input, formation, penetration, electricity consumption, etc.). Experimentally, it is rather difficult to select the parameters of the feedback settings, since in practice various types and diameters of the electrode wire are used, different process modes are used, etc.
Conclusions.

1. The control system for the arc welding process with a dosed pulse feed of the electrode wire, which includes a mathematical representation of the welding process, contains a substantially nonlinear link in the arc process current feedback loop, which can be linearized to study the system. In this case, for the problems of choosing the parameters for controlling the transfer of electrode metal, the method of harmonic linearization is most applicable, in which a nonlinear element can be represented by an asymmetric relay link.

2. The study of the developed control system can most expediently be carried out using the methods of operational calculus, the use of which makes it possible to obtain results applicable in design and technological practice, and determining the results of the arc process.

3. Verification of the applied research methods of the developed control system of the welding process with the use of a dosed feed of the electrode wire carried out using computer simulation and obtaining characteristic oscillograms confirms the adequacy of the selected research methods.

Conflicts of interests. The authors declare no conflict of interest.

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Fig. 4. Comparative results of the study of the arc welding and surfacing process: a – current of the conventional process; b – current of the process with dosed electrode wire feed; c – modelling of the welding process (qualitative representation)
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