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DESIGN OF AN UNIVERSAL SOURCE FOR SEMI-AUTOMATIC AC WELDING AND INDUCTION HEATING

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This paper proposes a circuit solution and a power source control algorithm for semi-automatic AC welding with improved energy and weight-size characteristics. A distinctive feature of the designed source is the absence of an input rectifier: welding is carried out with a high-frequency alternating current. That has made it possible to significantly reduce power losses in the source, as well as provide the possibility of implementing induction heating by connecting an inductor to the source output.

Another distinctive feature of the designed source is an increased power factor and a reduced level of higher harmonics of the current consumed. The power factor of the described source reaches 0.94 against 0.5÷0.7 for sources equipped with a conventional rectifier with capacitive smoothing.

The designed source's composition includes a power supply system for the wire feed drive with speed stabilization due to positive feedback on the motor current. That has made it possible to ensure the stable operation of the drive in a wide range of speeds. A model has also been developed of a flux wire welding torch containing a feed drive and a coil with a wire (up to 100 mm in diameter), placed, in order to reduce the size, in the handle of the torch.

In addition to the welding function, the source makes it possible to solve the tasks related to induction heating and/or hardening of small parts; to that end, a compact inductor is connected to its output.

Tests of the source showed the feasibility of the proposed ideas and circuit solutions. The dimensions of the source are 190×107×65 mm; weight, 1.4 kg; output current, up to 120 A. The proposed technical solution enables the construction of small-sized, lightweight, universal, easy-to-use power supplies for semi-automatic welding with the option of induction heating

Keywords: semi-automatic welding, power source, induction heating, electric power quality, power factor, FCAW welding

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1. Introduction

Semi-automatic welding is widely used in the industry, construction, during repair work. Welding is carried out with a solid electrode or flux-cored wire, which is fed into the welding pool [1–3]. Typically, welding is performed in a protective gas medium (Gas Metal Arc Welding – GMAW, or Metal Inert Gas – MIG process), or with a self-protective flux-cored wire (Flux Cored Arc Welding – FCAW) [1–4]. To power the welding arc in semi-automatic welding, sources with a rigid output volt-ampere characteristic are used [2, 3]. This is because with a rigid characteristic of the source, there is a self-regulation of the arc length. In this case, the average welding current is determined by the feed rate of the welding wire. Welding is carried out on direct current to ensure stable arc burning.

Thus, to enable the semi-automatic welding process, a power source with an adjustable output voltage and equipment for supplying electrode wire to the welding zone are needed. If the welding is carried out in a gaseous environment, then gas equipment is also necessary.

The power source and the drive of the electrode wire supply in most cases are combined in one device. It also hosts a gas supply valve with electrical control. This approach leads to the fact that the semi-automatic welding machine has significant dimensions and weight, which limits the mobility of the welder. If it is necessary to weld in hard-to-reach places, at a height, it is not always convenient and practical to take a large-sized heavy semi-automatic machine with you. One must use a burner with a long hose, which is also not always convenient.

In this regard, it is a relevant task to design sources for semi-automatic welding, which have a small mass and dimensions. To reduce the size of the source, it is advisable to devise new energy-efficient electricity converters, as well as remove the electrode wire supply drive from the source body. Moving the feed drive and wire coil directly into the burner eliminates the need for a flexible hose and reduces the required drive power. As a result, it is possible to design a compact welding semi-automatic machine at a low cost, whose application would be effective for small-volume work in hard-to-reach places that require the mobility of a welder.

2. Literature review and problem statement

Inverter welding power sources for semi-automatic welding are widely used. They have smaller dimensions [2] and weight [3] than sources with welding low-frequency transformers, as well as better adjustment properties [4], which makes them more convenient to work with. However, their mass and size limit the use of these sources. The relatively large weight and dimensions of semi-automatic machines are dictated by the fact that they must host gas equipment and a wire feeder with a replaceable coil. The mass of the inverter semi-automatic machine is typically quite large (one of the lightest at 12.8 kg is Tesla Weld FCAW 240 (Ukraine) [5], only for coils with a diameter of up to 100 mm; 11 kg – Edon SMARTMIG 275 (China) [6]; 14 kg – Kaiser ARC-FLUX 120 (China) [7]), which still limits the mobility of the welder.

It is possible to do without gas equipment through the use of flux wire, which makes it possible to weld without protective gas [8]. It is convenient to use it when working at height or in cramped spaces [9]. That is due to the fact that under such conditions, it is difficult to deliver a semi-automatic machine with gas protection.

In addition, it is possible to arrange the wire feeder drive directly in the burner [10]. The coil with electrode wire can also be placed in the burner, limiting to using only coils of small diameter (up to 100 mm) and weighing up to 0.5 kg. Arranging the coil and feed drive in the burner can significantly reduce the dimensions of the latter since the drive does not need to push the wire through the burner hose, which has a length of about 3 m. In addition, the size of the power source is also reduced.

There are battery-powered MIG/FCAW welding solutions in the market [11] that are simply a welding torch with a wire feed drive. However, such systems do not even have a welding current regulator. Note that they are popular not only in their civilian market niche but also for military operations.

The ability to use the laws of change in the parameters of the welding process is one of the main requirements for a modern source of welding current since it makes it possible to control the depth of melting [12] and the dimensions of the welded joint [13]. Therefore, it is also necessary to take into consideration the need to change the power factor, which was not done in the above works.

In addition to ensuring acceptable parameters of the welding process, under modern conditions the power source is also subject to the requirements for compliance with current electromagnetic compatibility standards [14, 15]. It should be noted here that most sources in the market for semi-automatic welding do not meet the emission standards of higher current harmonics by technical means [16]. Thus, when designing new equipment, attention should also be paid to the issue of electromagnetic compatibility [17].

Paper [18] analyzes the spectrum of current consumption of a typical welding inverter and substantiates the need to use means of correcting the power factor and reducing the level of harmonics of the current consumption in such equipment. Thus, document [19] sets out basic recommendations for the selection of equipment and requirements for filtering harmonics in the distribution networks of enterprises. Well-known manufacturers of welding equipment, in particular Lincoln Electric, also pay attention to electromagnetic compatibility and accounting for losses, including financial ones, due to a decrease in the quality of electricity [20].

Paper [21] proposes a solution to the problems of emission of higher harmonics through the use of specialized hardware – active filters. In [22], a circuit solution for the source is proposed, in which the issues of filtering higher harmonics are solved schematically and algorithmically. In the first case, the solution requires financing new equipment, in the second, the cost of the source increases.

Paper [23] proposes an original circuit solution for a welding inverter with a bridgeless power factor corrector based on SEPIC topology. The scheme is distinguished by a small number of active power components in the main power circuit but the modes of their operation are accompanied by the action of increased voltages, which leads to an increase in the requirements for the components and an increase in the cost of the welding source.

To reduce the cost of equipment, circuit solutions are designed in which the conversion of the ac voltage of the network into the output dc with galvanic isolation and power factor correction is performed in one direct converter [24]. Schemes with direct conversion are not widely used in welding equipment due to various difficulties in controlling and ensuring the stability of the welding arc burning.

Another issue is the impermanence of the load of the welding source. In the process of welding, the mode of operation of the latter changes from idle to short circuit in a very short time. Thus, with semi-automatic welding in a carbon dioxide environment, the frequency of short circuits can exceed 100 Hz. In addition, a similar frequency range is used to generate controlling mechanical effects, both for wire [25] and for tape [26] electrodes. In [27], control over the transfer of the electrode metal is used in multi-electrode surfacing. However, the issues of changing the mode of operation and, accordingly, the requirements for the operation of the power source were not considered. In this regard, research is relevant in the field of improving the algorithms for controlling converters as part of welding sources. For example, paper [28] addresses the development of effective methods for controlling a three-phase power factor corrector, taking into consideration the non-stationary nature of the load in the form of a welding arc. In [29], a variant of constructing a single-phase rectifier with an increased power factor, characterized by a small number of components, was proposed.

All this allows us to assert that it is a relevant task to undertake a study aimed at designing energy-efficient sources with an increased power factor and good dynamics of output current regulation.

3. The aim and objectives of the study

The aim of this work is to design a small-sized universal source for semi-automatic welding with an additional possibility of working with an inductor of comparable power, which would solve the task of induction heating. In this case, the source must have a reduced level of harmonics in the current consumed from the network, that is an increased power factor. This could make it possible to reduce the current load on the power source network and/or ensure the operation of more sources at the same network current load.

To accomplish the aim, the following tasks have been set:

– to build a scheme of the power part of the source and model it;

– to design a small-sized wire feeder for semi-automatic welding;

– to conduct an experimental study of a source with a high-frequency output for semi-automatic welding;

– to test the source under the mode of induction heating and study its energy parameters.

4. The study materials and methods

During the development and creation of an experimental source sample for semi-automatic welding, known methods for calculating and modeling electrical circuits were used. Of the theoretical methods, a symbol method for calculating sinusoidal current circuits was used; Laplace's mathematical apparatus of the transformation; methods for analyzing the frequency characteristics of electrical circuits; methods of analysis and synthesis of automatic control systems. The Mathcad software package (USA) was used for calculations.

The program for the source microcontroller was developed using the freely distributed programming environment in the C++ language.

During the experiments, we measured the power consumption of the source by the Feron TM55 wattmeter (China), which makes it possible to measure the effective voltage, acting current, active power, power factor. The output current of the source (due to the difficulty of measuring it directly) was estimated using a high-frequency 750:1 current transformer and the oscillograph DSO-1202B (China). The same oscillograph was used to debug the source and check the adequacy of mathematical models to a real experiment.

We measured dc voltage in the source control circuits using the multimeters M890D (China), DT890 (China).

The quality of the weld joint was assessed by comparison with the welds obtained during welding with the TEMP-059M semi-automatic machine (PDU-150-U3-220) (Ukraine) under similar modes and with the same materials.

5. Results of studying and modeling a source for semi-automatic welding with alternating current

5. 1. Development of the scheme for a power part of the source and its modeling

When tackling the task of building small-sized (and, therefore, convenient) welding sources, it is proposed to power the arc with high-frequency alternating current, which makes it possible not to install a welding current rectifier and reduce energy losses in the source. At the same time, the stability of arc burning does not deteriorate due to the fact that at a high frequency the current change rate is large and the arc gap does not have time to deionize (its time constant is 10^{-5}÷10^{-4} s). However, the problem is that the inductance of the welding circuit (it has the order of several μH) represents a large reactance at typical conversion frequencies (30÷100 kHz), which makes it necessary to provide a large no-load voltage of the source. This problem can be solved by installing a capacitor source in series with the output, which, together with the inductance of the welding circuit and the inductance of the scattering of the power transformer, forms a sequential resonant circuit. The arc current is regulated by changing the frequency.

To increase the power factor of the source, it is necessary to control the shape of the curve of the current consumed from the network. The use of a power factor corrector makes it possible to solve this problem but significantly increases the cost of the source. In fact, in its composition, there is another converter, designed for the full power of the source.

Another option is to use passive power factor correction circuits that do not require the introduction of power electronic keys into the circuit. One of these solutions was taken as a basis for the development of the source scheme, namely, the Valley Fill rectifier was applied.

The scheme of the power part of the designed source is shown in Fig. 1.

The source consists of a rectifier made according to the "Valley Fill" scheme (elements BR1, VD1...VD3, C1, C2, NTC1) [17, 18], loaded on a half-bridge resonant inverter [19]. The mains voltage is rectified by a diode bridge BR1 and enters the diode-capacitive stage VD1...VD3, C1, C2, NTC1. Capacitors C1 and C2 charge when they are connected in series via VD2 and NTC1. Thermistor NTC1 is used to limit the amplitude of the pulse of the initial charge current of the capacitors when the source is plugged into the network. It should be noted here that due to the use of the Valley Fill circuit, the charge and discharge circuits of the capacitors are separated, which made it possible to use a thermistor to limit the charging current without the need to install a powerful shunt relay. In commercially available sources, charge circuits operate with full operating current, which forces the use of an additional relay for bypass shunting elements of the initial charge current limitation.

The discharge of capacitors C1 and C2 occurs when they are connected in parallel through the diodes VD1 and VD3. The voltage on C1 and C2 is maintained at half the amplitude of the input (mains) voltage. Thus, at $|u_{\text{mains}}|>0.5U_m$ (U_m is the amplitude of the mains voltage), the VD1 and VD3 diodes are closed and the load (VT1VT2C3C4 half-bridge) is powered directly from the network through the BR1 bridge. If $|u_{\text{mains}}|<0.5U_m$, the load is powered by capacitors C1 and C2 via VD1 and VD3. The diagram of the Valley Fill output voltage of the rectifier is shown in Fig. 2.

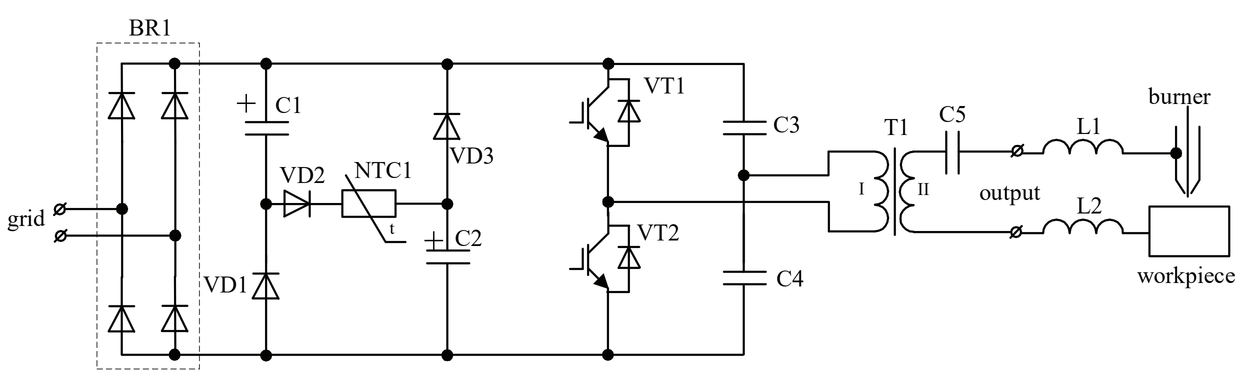

Fig. 1. Diagram of the power part of the source

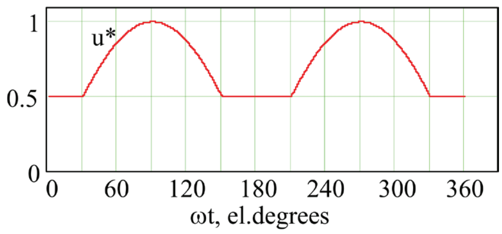

Fig. 2. Rectifier output voltage

The amplitude of mains voltage in Fig. 2 is taken as a unit.

Because most of the time the load is fed directly from the network, it becomes possible to control the shape of the current consumption curve by modulating the active power of the inverter. This makes it possible to increase the power factor of the source and reduce the current consumed from the network by reducing inactive power. At the same time, power modulation has almost no effect on the welding process due to the thermal inertia of the molten metal of the welding pool. At the same time, the energy reserve of capacitors C1 and C2 makes it possible to maintain arc burning (the "standby" arc mode) during the intervals of the transition of the mains voltage through zero.

The rectified voltage is supplied to a half-bridge inverter made on transistors VT1 and VT2. It is loaded on the primary winding of the high-frequency power transformer T1. Capacitors C3 and C4 form a midpoint at a high frequency. The secondary winding T1 is connected to the output terminals via the C5 resonant power capacitor.

In semi-automatic welding, welding cables are connected to the source outlet connecting the output terminals to the torch and the product. The inductance of welding cables is shown in Fig. 1 by throttles L1 and L2.

The half-bridge operates with a fill factor of 50 %, with the variable parameter being frequency. Its output voltage is in the form of a meander. As is known [20], such a signal can be represented as a Fourier series containing harmonics with odd numbers.

To analyze the processes occurring in the converter, we shall use the substitution scheme shown in Fig. 3.

In Fig. 3, the following designations are adopted:

– L_1, L_2 is the inductance of the primary and secondary windings T_1, respectively;

– L_M is the partial inductance of T_1 windings;

– C_R is the resonant capacity (corresponds to capacitor C_5 in Fig. 1);

– L_H is the load inductance (corresponds to L_1+L_2 in Fig. 1);

– R_H is the equivalent active load resistance (arc);

– e_1 is the half-bridge inverter output voltage.

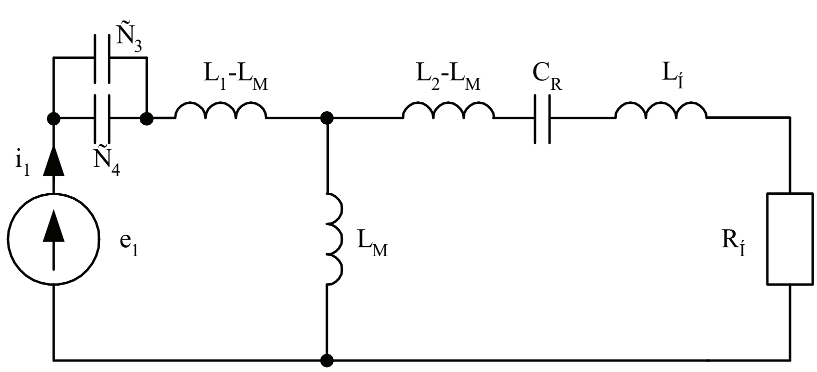

Fig. 3. High-frequency part replacement scheme

For analysis, it is convenient to use the method of calculation by the basic harmonic since the output circuit of the source has a pronounced resonant character ($C_R L_H$ circuit, Fig. 3). Therefore, the stable operation of the proposed source for welding with high-frequency current is possible only if there is effective automation to maintain the required current regime.

A welding arc with sufficient accuracy for practical calculations on the basic harmonic can be considered an active resistance, given that the arc gap does not have time to deionize during the transition of current through zero. In Fig. 3, the arc is represented by an equivalent resistance R_H. Since in semi-automatic welding the arc voltage is 12...18 V at 100...180 A, R_H has the order of tenths of an ohm (0.05...0.2 Ohm).

Let us denote the operator resistance of the elements on the right in the scheme from L_M (Fig. 3) as $Z_H(s)$, where s is the Laplace transform parameter:

$$Z_H(s) = (L_2 - L_M + L_H)s + \frac{1}{C_R s} + R_H. \quad (1)$$

Find the resistance on which the source e_1 is loaded:

$$Z_1(s) = (L_1 - L_M)s + \frac{1}{(C_3 + C_4)s} + \frac{L_M s \cdot Z_H(s)}{L_M s + Z_H(s)}. \quad (2)$$

Then the output current of the half-bridge is to be determined as:

$$I_1(s) = \frac{E_1(s)}{Z_1(s)}. \quad (3)$$

Since in the substitution scheme (Fig. 3) there is only one active resistance, the resistor R_H, then, using the balance of active power, it can be recorded that all the active power developed by the EMF (electric arc welding) source will be released in R_H. However, since R_H is the resistance of the arc, this power will be useful. Then, for the sinusoidal mode with an angular frequency ω, one can write:

$$P(\omega) = \mathrm{Re}\left(E_1(j\omega) \cdot \tilde{I}_1(j\omega)\right), \quad (4)$$

where $\tilde{I}_1(j\omega)$ is the conjugated current complex I_1.

Fig. 4 shows plots of the dependence of the output power on the voltage frequency of the EMF source e_1 (Fig. 3) at different load resistance R_H. The parameters of the circuit in the calculations are as follows: L_1=2.44 µH, L_2=152 µH, L_M=608 µH, L_H=2 µH, C_3=C_4=9.4 µF, C_R=1.35 µF. At the same time, the current limit I_1 at the level of 50 A is implemented. The construction implied the frequency range of 40...120 kHz. These parameters correspond to the experimental source described below.

Fig. 4 shows that by changing the frequency, it is possible to adjust the power released in the load within a wide range. In practice, the lower limit of the operating frequency is determined by the saturation condition of the magnetic core of the power high-frequency transformer. The upper limit of the operating frequency is limited by several factors: these are the loss of switching in the power keys, the speed of the control system, and the loss of remagnetization of the transformer core.

It is easy to see that the power in the load during frequency control cannot be reduced to zero. However, this is not an issue when solving the problem of powering the welding arc since semi-automatic welding is not performed at very low currents.

The switching of half-bridge transistors (VT1, VT2 in Fig. 1) should be carried out with a current-free pause necessary to prevent "through" currents. Fig. 5 shows the signal diagrams in the designed source.

The control signals of the upper (VT1) and lower (VT2) transistors are shown conditionally with positive and negative polarity. Between the closing of one transistor and the opening of the other, a current-free pause DT is maintained.

Since the load of the half-bridge has a pronounced resonant character (Fig. 4), the shape of the output current of the half-bridge has a form close to the sinusoidal.

Since the welding mode can be accompanied by rapid changes in load resistance (from breakage to short circuit), the control system must respond quickly to perturbation effects and effectively stabilize the output current of the half-bridge.

To measure the output current in the experimental source, synchronization of the analog-to-digital converter (ADC) with the moments of switching transistors is used. Current signal sampling is made at 4 times the output frequency, at intervals of 90 electrical degrees. In Fig. 4, they are designated as i_0...i_3. Assuming the output current of the half-bridge $i_1(t)$ is sinusoidal

$$i_1(t) = I_{1m}\sin(\omega t + \phi), \tag{5}$$

where I_{1m} is the output current amplitude, A;

ω is the output current angular frequency, s^{-1};

φ is the starting phase.

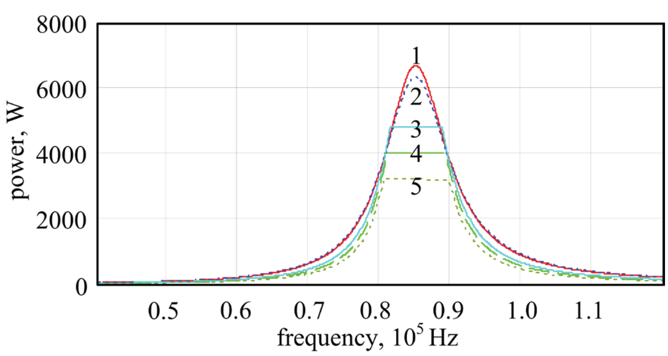

Fig. 4. Plots of the dependence of the output power on frequency at different load resistances R_H: 1 – 0.17 Ohm; 2 – 0.18 Ohm; 3 – 0.12 Ohm; 4 – 0.1 Ohm; 5 – 0.08 Ohm

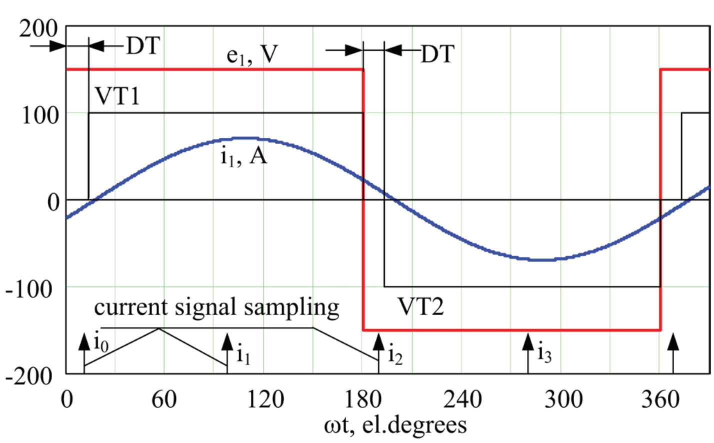

Fig. 5. Signal diagrams in the source scheme

One can write expressions for current samples as follows:

$$i_0 = I_{1m}\sin(\omega\cdot T_{SH} + \phi); \tag{6}$$

$$i_1 = I_{1m}\sin\left(\omega\cdot T_{SH} + \frac{\pi}{2} + \phi\right); \tag{7}$$

$$i_2 = I_{1m}\sin(\omega\cdot T_{SH} + \pi + \phi); \tag{8}$$

$$i_3 = I_{1m}\sin\left(\omega\cdot T_{SH} + \frac{3\pi}{2} + \phi\right), \tag{9}$$

where T_{SH} is the sampling-storage time of the ADC, s.

It is easy to see that $i_0=-i_2$, and $i_1=-i_3$. One can also rewrite an expression for i_1 as:

$$i_1 = I_{1m}\cos(\omega\cdot T_{SH} + \phi). \tag{10}$$

Then, according to the data of current samples, one can write:

$$4I_{1m}^2 = (i_0 - i_2)^2 + (i_1 - i_3)^2; \tag{11}$$

$$\omega\cdot T_{SH} + \phi = \mathrm{arctg}\frac{i_0 - i_2}{i_1 - i_3}. \tag{12}$$

Thus, for four samples per period, the amplitude and phase of the output current are calculated. Strictly speaking, two samples taken at intervals of 90 electric degrees would suffice [30, 31]. However, due to the presence of scaling circuits at the input of the ADC, a constant component is added to its input signal, which is necessary to work on the linear section of the ADC transfer characteristic. This constant must then be removed programmatically but using the two expressions above to estimate amplitude and phase eliminates this step because only paired sample differences are present in these expressions.

The calculated amplitude of the current I_{1m} is used to compare with the setting and determine the necessary displacement of the frequency ω. The phase is used to determine the nature of the output current: inductive (that is, working at a frequency above the resonance) or capacitive (otherwise).

It should be noted here that from the amplitude-frequency response of the load shown in Fig. 4, it follows that the same current can be obtained at two different frequencies: one below the resonant frequency, the second above. However, given the peculiarities of the power components (transistors and antiparallel diodes), it is energetically more profitable to work at frequencies exclusively higher than the resonant one in order to avoid additional losses due to the reverse restoration of antiparallel diodes. To satisfy this condition, the output current sign must be positive when the upper transistor is closed and negative when the lower transistor is closed, and the current sign must not change during the current-free pause. In an experimental source, this is achieved by working exclusively at frequencies above the resonant frequency of the system. In this case, the phase of the output current is calculated taking into consideration not only the duration of the current-free pause DT and the time T_{SH} but also the time of signal propagation in the transistor control circuits, as well as the recharge time of the capacities of their gates. The general structure of the converter control system is shown in Fig. 6.

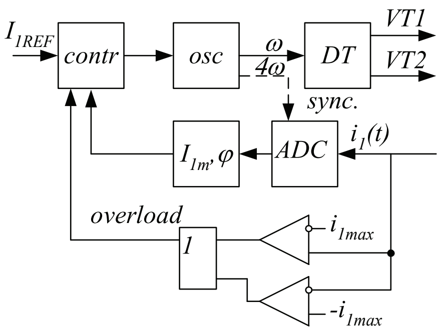

Fig. 6. Converter control system structure

In Fig. 6, I_{1REF} signal is the output current setting. The controller and the calculation unit I_{1m}, φ are made in the form of a microcontroller program. The controlled generator and the *DT* current-free break generator are implemented on the onboard hardware timer. There is also high-speed overload protection of the converter, made on two comparators and a 2OR logic element. When the conditions $i_1(t)>I_{\max}$ or $i_1(t)<-I_{\max}$ are met, both power transistors are immediately switched off before the end of the output frequency period, and the controller in this situation quickly increases the frequency of the generator.

In normal operation (when $|i_1(t)|<I_{\max}$), the controller maintains the output current by changing the frequency of the generator. To increase the power factor of the source at output currents below the maximum, the modulation I_{1REF} is performed in proportion to the square of the rectified network voltage.

5. 2. Design of a small wire feed drive for semi-automatic welding

The wire feeder is of small size and is placed in a torch. The mechanical part of the drive consists of a DC motor with excitation from permanent magnets, a gearbox, and a feed roller, to which a welding wire is pressed with a passive roller. Since a small-sized low-power engine was used, the task arose to stabilize its rotation speed during fluctuations in the momentum of load on the shaft. Since the installation of any speed sensors would lead to a complication of the mechanics of the drive and an increase in its dimensions, a speed controller with positive feedback on the armature flow is used. Its structural diagram is shown in Fig. 7.

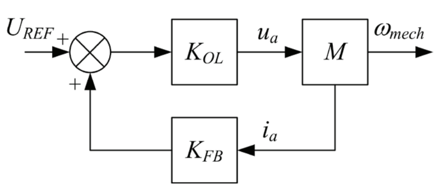

Fig. 7. Structural diagram of the speed controller

The controller contains an amplifier (a link with a K_{OL} transmission coefficient), the output of which is connected to the motor armature *M*. The voltage at the armature is indicated as u_a. A signal proportional to the current of the motor armature (i_a) through the feedback circuit (the link with the transmission coefficient K_{FB}) enters the input adder, which is also fed the signal of setting the speed U_{REF}.

It is known from the theory of electrical machines [30] that in order to maintain the speed of a DC motor of independent excitation, it is necessary to stabilize its EMF of the armature which is defined as

$$e_a = C\Phi\omega_{mech}, \quad (13)$$

where $C\Phi$ is the structural coefficient, V·s;

ω_{mech} is the mechanical shaft speed, s^{-1}.

On the other hand, the EMF of the armature can be expressed as

$$e_a = u_a - i_a \cdot r_a, \quad (14)$$

where u_a is the voltage at the armature, V;

i_a is the armature current, A;

r_a is the armature resistance, Ohm.

Controller with the structure shown in Fig. 7 provides the formation of a voltage at the armature, defined as

$$u_a = \left(U_{REF} + K_{FB} \cdot i_a\right) \cdot K_{OL}. \quad (15)$$

It follows from the last two expressions:

$$e_a = \left(U_{REF} + K_{FB} \cdot i_a\right) \cdot K_{OL} - i_a \cdot r_a. \quad (16)$$

If the equality $K_{FB} \cdot K_{OL} = r_a$, is ensured, the EMF of the armature will be determined as $e_a = U_{REF} \cdot K_{OL}$ and not depend on the armature current. This circumstance is used to stabilize the speed of the engine during fluctuations in the momentum of load on the shaft.

In the experimental sample, the feed rate controller is implemented on the LM358 operational amplifier, and the output motor control stage is made on the MC34063 pulse converter, which provides an output current of at least 1 A. The use of a pulse converter has made it possible to improve the efficiency of the controller, abandon the heatsink, reduce the size of the board, and place it directly near the motor, in the burner handle. The dimensions of the controller board are 30×35 mm.

5. 3. Results of the experimental study of a source with high-frequency output for semi-automatic welding

We have designed and manufactured an experimental sample of an inverter power source with a high-frequency output (current up to 120 A, source dimensions of 190×107×65 mm, weight 1.4 kg), in which an additional option for working with an inductor is implemented. A photograph of the source is shown in Fig. 8.

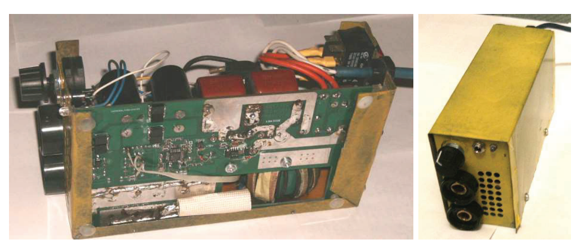

Fig. 8. General view of the experimental source

Source control is implemented on a single-chip microcontroller STM32F072C8T6, which has a 32-bit ARM core with a clock frequency of up to 48 MHz and developed peripherals (DACs, comparators, timers, ADC). The power part uses SGT40N60NPFD transistors, controlled from the IRS2186 driver. To measure the output current of the half-bridge, the current transformer AS-105 with a transformation ratio of 750:1 was used. The power transformer is wound on the toroidal ferrite core T50/30/20 and contains 20 turns in the primary winding and 5 turns in the secondary winding. The resonant capacitor is composed of 5 metal-film capacitors MKPH 0.33 µF×1,200 V, connected in parallel.

The source also provides an isolated non-stabilized output of 15 V 1 A for connecting the speed controller of the electrode wire feed drive.

Under the semi-automatic welding mode, the tests were carried out with AWS E71T-11 flux-cored wire with a diameter of 0.9 mm on a cassette with a capacity of 0.5 kg. The recommended welding current for this wire is 100...130 A, which agrees well with the parameters of the source. The tests showed a stable arc burning and stable formation of the weld when welding with a high-frequency current. A sketch of a torch for semi-automatic flux-cored wire welding is shown in Fig. 9.

Flux-cored wire is fed into the welding zone using a nozzle (pos. 1), where the current supply is located, through the mouthpiece (pos. 2). The feed drive (pos. 6) is controlled by a button (pos. 3) located on the handle of the burner (pos. 4). The feed drive (pos. 5) together with the cassette (pos. 6) is attached directly to the burner body, in its rear part, which increases the mobility of the device. The feed drive is powered by means of a control cable (pos. 7). The welding current is supplied to the burner by a power cable (pos. 8).

The drive control system is made in accordance with chapter 5. 2; the drive board is located in the handle of the burner.

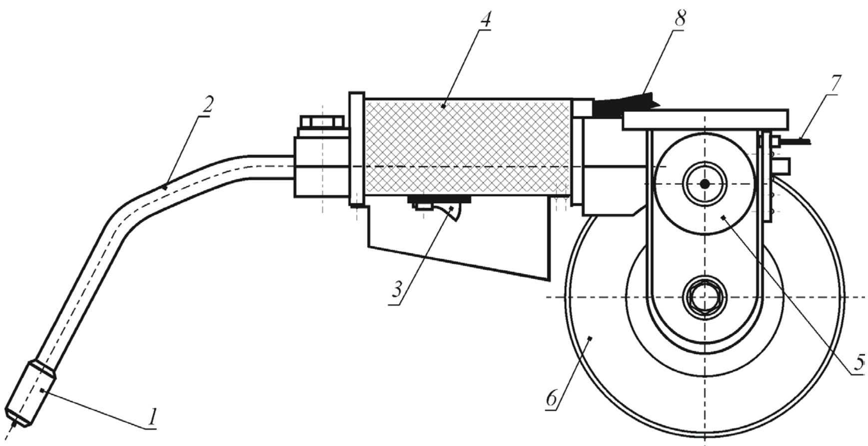

Fig. 9. Flux-cored wire welding torch

5. 4. Results of testing the source under the mode of induction heating and of studying its energy parameters

Additional resources for increasing the resistance of products and tools are provided by heat treatment of welded and welded seams with a gradient of physical, mechanical, and operational properties along the width of the seam or the height of the welded layer. The working layer acquires qualitative characteristics close to composite materials [30].

The use of tools for local heat treatment will expand the functionality of welding equipment and the range of solvable technological tasks. Since the designed source has an AC output, it is possible to connect an inductor to it to solve the problems of induction heating. No changes in the algorithm of the controller are required at all. The condition for normal operation with the inductor is only to obtain a resonant frequency of the circuit in the range of 40÷90 kHz. At a lower resonant frequency, it will be impossible to reach the required power, with a larger frequency, there will be a very small control range.

For tests under the induction heating mode, an inductor made of copper uninsulated wire with a diameter of 4.3 mm and containing 5 turns with a diameter of 60 mm, a winding length of 35 mm was connected to the source. A photograph of the inductor is shown in Fig. 10.

Fig. 10. Photograph of the inductor used in the experiments

Measurements of power consumption from the network showed that the source generates a power of more than 2 kW under a maximum mode. The output frequency was about 70 kHz.

In the future, it is possible to implement the mode of induction heating at the third harmonic, which will make it possible to cover the range from 40 kHz to 360 kHz (40÷120 kHz – the usual mode on the first harmonic, 120÷360 kHz – operation on the third harmonic).

The power factor of the designed experimental source is 0.9÷0.95, depending on the output power (measured by the Feron TM55 device). This is significantly better than the indicators of commercially available sources, which have a power factor in the range of 0.5÷0.7. Thus, the current consumed from the network of the described source is 1.3÷1.6 times less than that of the existing ones, with the same active power. This property makes it possible to use the designed source in "weak" networks, with a large length of the network wire (with extension cords), and to ensure the possibility of simultaneous operation of more sources with the same network current load.

6. Discussion of results of studying the designed source

A small-sized source for semi-automatic welding and an electrode wire feeder, combined in one unit with a torch, have been designed. An experimental sample of such a source was assembled and tested. The possibility of implementing semi-automatic welding on high-frequency alternating current has been proven; expectations for the power factor of the designed source have been confirmed.

Our results are explained by the fact that when creating a source, modern methods of synthesis of converter control systems were applied, a modern element base was used (Fig. 1, 6). All this has made it possible to build an energy-efficient small-sized source at a small cost.

A feature of the proposed and implemented method is that welding is carried out with a high-frequency alternating current. All known sources use direct current or low-frequency alternating current. The proposed method of welding with high-frequency alternating current is possible only when taking into consideration the inductance of the welding circuit (welding cables). In this regard, a scheme of a resonant welding inverter and a method for controlling it have been developed, which ensures stable operation under the conditions of changing parameters of the welding circuit. The source constructed is characterized by minimal dimensions and weight (Fig. 8) due to the elimination of the output rectifier and arranging the electrode wire feed drive along with the controller and coil directly in the burner. This distinguishes it from the commercially available semi-automatic machines [6–8]. The structure of the burner is similar to ReadyWelder [12]. The power factor of the designed source is slightly lower than that of sources with a power factor corrector. Nevertheless, the applied circuit-algorithmic solution has made it possible to abandon the introduction of additional power active and passive components into the main power chain, which made it possible to minimize the weight and size characteristics of the source and its cost.

An additional induction heating option allows the same source to solve tasks such as hardening small parts or locally warming up threaded connections to facilitate their unscrewing.

The limitations in the operation of the source include the inability to work with long (more than 3 m) welding cables due to their high inductance. However, in practice, this is not an issue since the source is portable and there is no point in using long welding cables with it. The possibility of using the designed source for manual arc welding with a coated electrode (MMA process) was also tested. To this end, a transformer with an increased secondary voltage was fabricated to ensure a stable ignition of the arc (Fig. 1, 3). Our experiments have shown that the arc lights up and burns stably when powered by a high-frequency current (Fig. 4). However, the electrode wire, due to the skin effect, overheats very quickly. That leads to overheating and burnout of the electrode coating, as well as a loss of rigidity of the electrode wire. For this reason, it is advisable to use the designed source for welding techniques involving a small electrode reach, that is, for semi-automatic welding.

The disadvantages of the designed source in the presented version include the instability of the voltage at the arc interval, which leads to an unstable arc length during welding. This is because the adjustable quantity is the welding current, rather than the voltage in the arc gap. In the future, it is possible to develop a modified converter control algorithm, which could provide voltage control at the arc interval, which would stabilize the arc length and improve the stability of the weld formation process.

7. Conclusions

1. A scheme of the power part of the source was developed; its modeling was carried out. We have built a small-sized welding power source using a high-frequency alternating current. The application of the proposed principle of source construction for semi-automatic welding with high-frequency alternating current can significantly improve the weight and size characteristics of the source (reducing the volume by 1.5÷2 times). In addition, the circuit solution makes it possible to reduce power losses in it by 40÷50 % by eliminating the output rectifier. This makes it possible to improve the convenience of welding and increase the mobility of the welder.

2. A small-sized wire feeder for semi-automatic welding has been designed. The drive is structurally combined with the burner and provides regulation of the speed of supply of electrode wire within a wide range through the use of a specialized motor control circuit.

3. We have performed an experimental study of the source with a high-frequency output for semi-automatic welding. The operability of the proposed circuit solutions and control algorithms has been experimentally proven.

4. Tests of the source under the mode of induction heating and the study of its energy indicators were carried out. The proposed circuit solution of the source makes it possible to increase its power factor from (0.5÷0.7) to (0.9÷0.95) by reducing the consumption of inactive power from the network. This makes it possible to reduce the current load on the network or increase the number of simultaneously operating sources with the same load on the power source. The possibility of implementing the induction heating process expands the scope of application of the designed source and increases its versatility.

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