Розроблено однофазні інверторні зварювальні джерела живлення (прямоходовий і мостовий) з підвищеним коефіцієнтом потужності. Відмінні риси джерел: відсутність додаткових силових індуктивних компонентів, знижена ємність конденсатора кола постійного струму, спрощена схема обмеження зарядного струму. Струм розроблених джерел на 30–45 % нижче, ніж у «класичних» інверторних джерел без коректора коефіцієнта потужності

Ключові слова: коефіцієнт потужності, зварювальний інвертор, джерело живлення, підпал дуги, стабілізація горіння дуги

Разработаны однофазные инверторные сварочные источники питания (прямоходовый и мостовой) с повышенным коэффициентом мощности. Отличительные особенности источников: отсутствие дополнительных силовых индуктивных компонентов, сниженная емкость конденсатора цепи постоянного тока, упрощенная схема ограничения зарядного тока. Потребляемый ток разработанных источников на 30–45 % ниже, чем у «классических» инверторных источников без корректора коэффициента мощности

Ключевые слова: коэффициент мощности, сварочный инвертор, источник питания, поджиг дуги, стабилизация горения дуги

UDC 621.341.572, 621.791.75
DOI: 10.15587/1729-4061.2017.106957

DEVELOPMENT OF SINGLE-PHASE HIGH-POWER FACTOR INVERTER WELDING SOURCES

V. Burlaka
PhD, Associate Professor*
E-mail: vburlaka@rambler.ru
E. Lavrova
PhD, Associate Professor**
E-mail: lavrova.e.v.pstu.edu@gmail.com
S. Podnebennaya
PhD, Associate Professor*
E-mail: podsvet@gmail.com
I. Zakharova
PhD, Associate Professor**
*Department of Metallurgy and Technology of Welding Production***
Department of Automation and Mechanization of Welding Production*
***State Higher Educational Institution «Priazovskiy State Technical University»
Universitetska str., 7, Mariupol, Ukraine, 87500

1. Introduction

The main trend in development of welding sources is an increase of the degree of interaction between the control object (welding arc, molten electrode metal and weld pool) and power supply. This makes it possible to improve the quality of the welding joint formation.

The basic requirements for power supplies for manual arc welding are related to the need for easy arc ignition and stability of its burning. Also, the task exists of elimination of the possible "sticking" of the electrode to the workpiece when trying to ignite the arc.

At the same time, the issues of the influence of the power supply on the mains, the influence of the quality of electricity on the quality of welding, including owing to the mutual influence of the sources, are often not concerned at all. Therefore, in the context of rising energy prices and introduction of standards for electromagnetic compatibility (EMC) of technical equipment, the actual task is to ensure EMC, improve energy efficiency and technical and economic parameters of welding equipment.

2. Literature review and problem statement

When developing welding sources, the objectives are to achieve high-power density, high efficiency, flexible output voltage-current characteristic (V-I characteristic), etc., but little attention is paid to the EMC of the supply with the power mains. EMC means:

– harmonic distortion of the input current (THD – Total Harmonic Distortion);

– power factor (PF), calculated in accordance with the IEEE 1459-2010 standard;

– level of high-frequency noise, etc.

Due to the high harmonics ratio in the input current, welding supplies are not entirely correct to be referred to energy-saving equipment [1–5]. In [1, 2], an analysis of the circuitry of welding inverter supplies was carried out, including from the standpoint of electromagnetic compatibility. In [3], the results of testing several welding supplies with an analysis of the quality of their input currents are shown. It is shown that inverter supplies are characterized by large distortions of the input current than supplies with low-frequency transformers. In [4, 5], the ways of increasing the technological efficiency of welding power supplies are outlined, but there is practically no attention paid to electromagnetic compatibility issues. At the same time, according to the information given in [6], electric welding equipment is about 65 % of potential sources of electromagnetic interference.

Nowadays, research in the field of welding power supplies is aimed at providing a high-power factor and EMC with the mains. Thus, in [7] a power supply based on a modified ZETA converter was proposed. Operation in the discontinuous current mode allows increasing the power factor of the supply. [8] describes the use of a converter with a SEPIC topology to increase the power factor of a power supply. Other researchers are also working on the development of the bridgeless power supplies [9]. Work is underway to develop welding sources with power factor correction based on the Canonical Switching Cell [10]. In [11], circuit solutions of active rectifiers with a unity power factor for power supplies with double energy conversion are presented. The main drawback of such sources is a slightly reduced efficiency and high technical complexity of the power conversion systems used.

In general, energy conversion at high frequency is used to increase efficiency and improve the mass-dimension parameters of welding sources for arc welding [12]. This leads to a reduction of the mass and size of the supply (up to 70 %, according to [13]), reducing the energy losses in the source, increasing the speed and increasing the range of adjustment of output parameters.

However, despite obvious advantages in terms of mass-size characteristics and efficiency, the developers paid insufficient attention to the problems of increasing the PF of inverter supplies. Thus, tests of single-phase inverter supply SELMA ARC-160 at power consumption of 1.1 kW and 3 kW showed that the supply PF varies from 0.652 (1,1 kW) to 0.702 (3 kW), and displacement power factor – from 0.992 (1.1 kW) to 0.998 (3 kW).

In practice, low PF of inverter supplies is explained by the high content of harmonics in the current consumption (THD is more than 100 %). This leads to increased mains power losses (these losses are inversely proportional to the square of the true PF in the first approximation), distortion of the main's voltage waveform.

It is also possible that overvoltages may appear in the mains due to resonances at high-order harmonic frequencies when welding inverters operate, and the voltage amplitude can reach 800 V [14].

The high harmonic distortion of the aforementioned inverter welding supply input current is explained by the structure of the power processing unit shown in Fig. 1, namely, the circuit of the AC-to-DC converter. Often this converter is a diode bridge with a high-capacity smoothing capacitor (for the SELMA ARC-160 supply its capacitance is about 2000 μF) at the output. Such power conversion principle is utilized in an overwhelming majority of widespread welding inverters of the budget class.

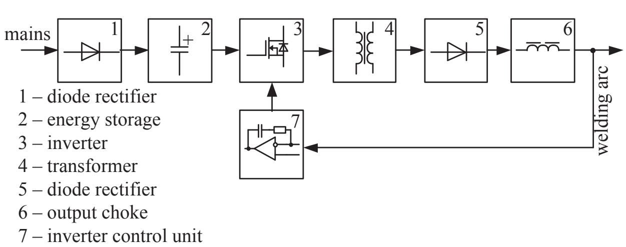

Fig. 1. A power processing diagram of the SELMA ARC-160 welding inverter

As is known, electrolytic capacitors, especially those operating under severe conditions (high current and elevated temperature), have a limited lifetime and require periodic replacement due to loss of capacity and growth of internal resistance. This circumstance somewhat reduces the reliability of inverter welding supplies, in the power circuits of which there are bulk capacitors with large stored energy. To limit the amplitude of the inrush charging current of the bulk capacitor when the supply is connected to the network, additional components are used in the power circuit. Usually, it is a power resistor and a relay with normally open contact, connected in parallel to this resistor.

The majority of the produced inverter welding sources do not have PF correction and do not meet the requirements of EMC standards for technical means (DSTU IEC 61000-3-2: 2004, DSTU EN 61000-3-12: 2014).

Undoubtedly, professional welding inverters that include an active power factor corrector (PFC) and satisfy modern EMC standards are also available [15–17]. The power processing diagram of such a welding power supply is shown in Fig. 2.

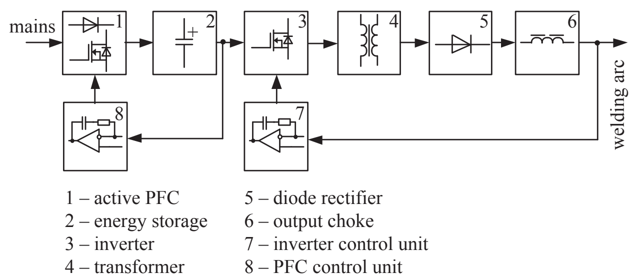

Fig. 2. The power processing diagram of the welding inverter with a power factor corrector

However, because of the high cost, which exceeds several times the price of a welding sources without a PFC, the distribution of such supplies is very much hampered. The high cost is due to the more complicated power processing in the supply with the PFC [18]. This makes it necessary to carry out further research and find ways to create new energy-efficient welding sources with improved technical and economic characteristics.

3. The aim and objectives of the study

The aim of the work is the development of inverter power supplies with increased PF having characteristics close to professional welding inverters, but having a lower cost.

To achieve this goal, the following tasks were accomplished:

– development of circuit topologies for AC/DC converters with input current control and galvanic isolation of the output by means of a high-frequency transformer;

– development of algorithms and control systems for converters in order to ensure maximum PF and, at the same time, forming a given output V-I characteristic of the supply;

– integration of service functions into control systems of the developed power supplies (i. e. arc boosting, «anti-stick», open circuit voltage limitation, etc.).

4. Ways to create supplies with increased power factor

Increasing of the supply PF is possible by providing direct control of the input current. Let us consider the application of direct conversion type supplies, the power processing scheme of which is shown in Fig. 3. In such supplies, direct conversion of the mains voltage to high-frequency voltage is used, followed by transformation and rectification. In such supplies, due to the use of special algorithms for converter control, it is possible to provide both input current control and formation of a specified output V-I characteristic of the supply.

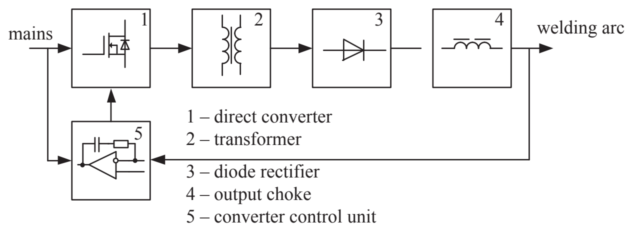

Fig. 3. The power processing diagram of a direct conversion type welding inverter

In direct type converters, there are usually no energy storage devices. In this case, for single-phase utility power, the instantaneous load active power will vary with a doubled mains frequency. However, for arc welding, this is not critical because of the thermal inertia of the weld pool. Nevertheless, it is necessary to prevent de-ionization of the arc gap during mains voltage zero-crossing, for example, by switching to the «sustain» mode of the arc with a small power.

Inverter welding sources (small and medium power) with increased PF have been developed. These sources have single-phase power input and ensure the maintenance of arc burning during mains voltage zero-crossing. The sources are built using the principle of direct conversion, have significantly reduced capacitance of the smoothing capacitor, and controlled input current.

4. 1. Welding source with a forward converter

The low-power welding source is made based on a forward converter, in which the magnetization and demagnetization circuits of the transformer are separated and one power switch is added. The circuit topology of the power part of the supply is shown in Fig. 4.

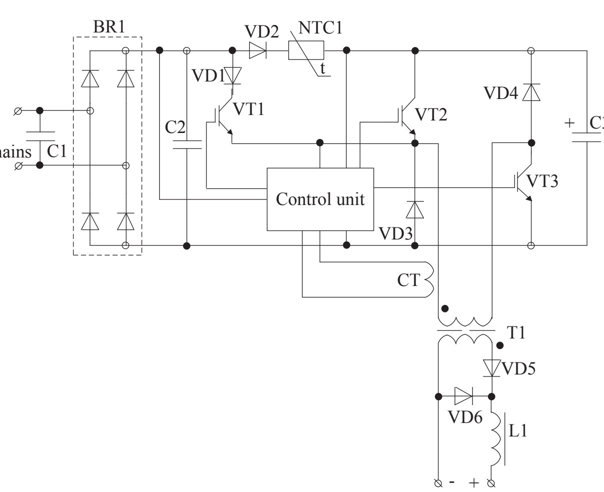

Fig. 4. Circuit topology of the power part of the developed supply with a forward converter

The elements VT2, VD3, VT3, VD4, C3, T1, VD5, VD6, L1 form a classical forward converter. The bulk capacitor C3 has a relatively small capacitance. This allowed its inrush charging current to be limited by a single NTC1 thermistor. The mains voltage is rectified by the input rectifier formed by the BR1 diode bridge. The blocking capacitors C1, C2 attenuate the penetration of high-frequency interference into the mains.

A distinctive feature of the developed supply are the elements VD1, VT1, VD2 set into the circuit. The presence of the VT1 switch allows supplying the primary winding of the power transformer T1 with rectified, but not smoothed, mains voltage. The diode VD2 thus prevents discharge of the storage capacitor C3 into the T1 winding. The diode VD1 serves to protect the transistor VT1 from the reverse voltage when VT2 is switched on. Such a topology of the power part allows for limited control over the waveshape of the input current drawn from the mains.

Demagnetization (reset) of the transformer takes place at an increased voltage (on the capacitor C3), and the magnetization (forward interval) takes place at a lower voltage (rectified mains voltage). This makes it possible to operate the converter with a duty cycle of more than 0.5. Thus, the duration of the forward interval can exceed half of the switching period. This circumstance allows increasing the range of welding source output voltage regulation.

The main power switches are VT1 and VT3, they are controlled synchronously. The forward interval of the supply begins when the switches are simultaneously turned on.

The duration of the forward interval is determined from the condition of proportionality of the local average current drawn from the mains to the magnitude of the rectified mains voltage. In this case, the rectified mains voltage at the output of the BR1 must be sufficient to maintain the load current. This provides a significant increase of the supply's PF. Since the power supply load (welding arc) is characterized by parameters instability, the control of the local average current consumption is performed by calculating the charge passed through the primary winding of the power transformer. A signal proportional to this charge is formed by integration of the secondary current of the current transformer installed in the primary winding circuit of the power transformer of the supply under consideration. Such a construction of the control system makes it possible to almost completely exclude the influence of the supply's output current ripple on the quality of the input current formation.

If the voltage at the output of the bridge BR1 is not sufficient to maintain the load current, the VT2 switch is turned on and the voltage from the storage capacitor C3 (via the C3-VT2-T1-VT3-C3 path) is applied to the T1 primary winding. Since this voltage is approximately equal to the amplitude of the mains voltage, this is sufficient to ensure the sustaining of the welding arc. Thus, for a small absolute value of the mains voltage, the supply goes into the «sustain» mode utilizing the energy stored in the C3 bulk capacitor.

The demagnetization interval of the supply begins with the turning off of all power switches (VT1-VT3). The energy, stored in the magnetic field of the transformer T1, is discharged into the storage capacitor C3. The current goes along the path: T1-VD4-C3-VD3-T1. In the secondary circuit, the diode VD5 turns off, the load current (L1 choke current) freewheels into VD6.

By discharging the energy of the transformer's T1 magnetic field into the capacitor C3, the voltage on the latter can be regulated to a level not lower than the amplitude of the mains voltage. This allows stabilizing the open-circuit voltage of the power supply and making it independent of the mains voltage, thereby facilitating the arc ignition.

4. 2. Experimental verification of a forward converter based welding source

An experimental welding source with an output current of up to 160 A has been created to experimentally confirm the above provisions. The capacitors: C1 – 6.8 μF × 630 V, C2 – 0.1 μF × 400 V, C3 – 330 μF × 450 V. The BR1 diode bridge – GBJ5010, the diodes VD1, VD3, VD4 – 30ETH06, VD2 – FR307, VD5, VD6 – 150EBU02. The transistors VT1, VT3 – FGH40N60SFD, VT2 – IRG4PC50W, the thermistor NTC1 – MF72-3D15. The transformer T1 is made using the ETD59/31/22 core with a non-magnetic gap of 1.4 mm, has a transformation ratio of 28/9, the inductance of the primary winding is 320 μH. The output choke L1 has an inductance of 30 μH at a current of 100 A. The supply of the control circuits is from a low-power TNY255P-based flyback converter powered from the capacitor C3. IGBT gate control signals are generated by a single-chip STM32F030F4P6 microcontroller (STMicroelectronics, Switzerland, China) that works with specialized FOD3184 drivers (Fairchild Semiconductor, USA, China).

To maximize the use of the magnetic core of the power transformer, the switching frequency of the power switches of the experimental supply is not fixed and is calculated in real time by the condition of stabilizing the amplitude of the flux linkage of the primary winding of the transformer. Variable frequency allows reducing dynamic power losses in power switches. Due to the weakening of the influence of the power transformer leakage inductance, it becomes possible to increase the maximum power of the supply. Due to the distribution of the electromagnetic interference energy over a larger frequency range, it is possible to reduce its spectral density.

The circuit also has a high-speed overcurrent protection of power switches with a fixed current reference. Protection provides current limitation at a small output voltage, including situations when the power supply output is short-circuited.

In the experimental power supply, the switching frequency of the power switches varies in the range of 15–63 kHz.

The static output V-I characteristic of the described power supply is hyperbolic (with constant power) within the operating range. This leads to the stabilization of the thermal power of the arc, the forcing of the arc is naturally realized (increase of the current with decreasing voltage, the «Arc Force» function). The arc ignition voltage of the experimental supply is 110–120 V and is independent of the mains voltage.

4. 3. Power supply with a full-bridge converter

Let us consider the developed medium power welding inverter based on a full-bridge converter. A distinctive feature of the power supply is the use of a Valley-Fill rectifier scheme (Fig. 5). The output voltage of the rectifier varies from 0.5 to 1 of the mains voltage amplitude with the ripple frequency that is twice the mains frequency.

If the instantaneous absolute voltage of the mains exceeds 0.5 amplitude, then the load (bridge inverter VT1 – VT4) receives power directly from the mains through the BR1 bridge. When the mains voltage absolute value exceeds the sum of the voltages on the capacitors C1 and C2, the latter charge through the diode VD2 and the NTC1 thermistor. The capacitor C3 is bypassing for high-frequency currents.

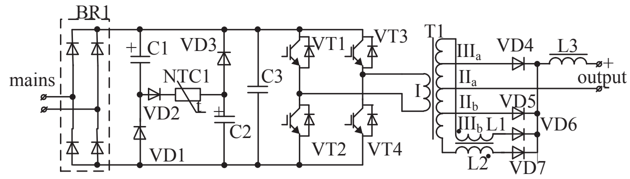

Fig. 5. Circuit topology of the power part of the developed supply with a full-bridge converter

If the absolute value of the mains instantaneous voltage is less than 0.5 amplitude, the load is supplied from the parallel-connected capacitors C1 and C2 through the diodes VD1 and VD3. The current drawn from the mains in this case is close to zero.

To approximate the waveshape of the input current (drawn from the mains) to the waveform of the mains voltage, the power supply converter control system is synthesized in such a way that the current consumed by it is proportional to the supply voltage.

Mathematical simulation shows that the maximum PF in this case is more than 0.97, and the THD of the input current is less than 25 %.

Assuming the mains voltage is sinusoidal $u(t)=U_m \sin(\omega t)$, the current consumed from the mains will be described by the equation

$$i(t)=\begin{cases} I_m \sin(\omega t), \text{ if } |u(t)|>0.5U_m, \\ 0, \text{ if } |u(t)|\le 0.5U_m, \end{cases}$$

where U_m, I_m are the amplitudes of the mains voltage and the load current, respectively, ω is the angular mains frequency. The theoretical maximum of the PF in this case is

$$PF_{\max}=\frac{\int_0^{2\pi/\omega} u(t)i(t)dt}{\sqrt{\int_0^{2\pi/\omega} u(t)^2 dt\cdot\int_0^{2\pi/\omega} i(t)^2 dt}}=$$

$$=\frac{\int_{\arcsin(0,5)}^{\pi-\arcsin(0,5)} \sin^2(\omega t)d(\omega t)}{\sqrt{\int_0^{\pi}\sin^2(\omega t)d(\omega t)\cdot\int_{\arcsin(0,5)}^{\pi-\arcsin(0,5)} \sin^2(\omega t)d(\omega t)}}=0.97,$$

and the harmonic distortion of the input current is of the order of

$$THD=\sqrt{\frac{1}{PF_{\max}^2}-1}\cdot 100\,\%=25\,\%.$$

Such a power supply topology makes it possible to significantly reduce the energy kept in the bulk capacitors. This leads to the size and cost reduction of the power supply. In addition, this avoids the use of special circuits for limiting the inrush charging current.

With the power supply topology described above, it becomes necessary to choose the transformer ratio of a power transformer in such a way as to ensure stability of arc burning during time intervals when the converter feeds from the bulk capacitors C1 and C2. In practice, this means the need to double the output voltage in comparison with conventional welding inverter circuits, which leads to an increase in the primary current of the power transformer and worsening of the operating conditions of the power transistors.

In the developed welding source, the voltage increase at the no-load condition and low-load currents is provided by an additional rectifier built using the diodes VD6, VD7 with reactive current limitation by the chokes L1, L2. In contrast to the known schemes with ballast resistors, this approach avoids additional losses of active power and maintains high converter efficiency.

If the output voltage of the inverter is a square wave with a frequency f, then the maximum current in the diodes VD6, VD7 at a continuous supply output current is equal to

$$I_{\max} = \frac{\dfrac{u_3}{2L_1 \cdot f}}{1 + \dfrac{u_3}{u_3 + 2u_2}},$$

where u_3 is the voltage at the additional winding $\mathrm{III_a}$ or $\mathrm{III_b}$ (these voltages are equal); u_2 – voltage on the winding $\mathrm{II_a}$ or $\mathrm{II_b}$ (these voltages are equal); L_1 – inductance of the choke L1 or L2 (they are equal).

When operating under load (with continuous output current in L3), $I_{\max}$ remains almost unchanged, that is, the presence of an additional rectifier (VD6, VD7) does not lead to a significant increase in the load on the inverter. The output current of the inverter is determined mainly by the reflected load current flowing through the diodes of the main rectifier VD4, VD5.

Since the chokes L1, L2 operate with a DC current component, they are wound on the same core to eliminate DC bias and are connected out-of-phase. The presence of mutual inductance between them does not have a significant effect on the operation of the circuit, since currents in L1 and L2 appear at different instants of time – they operate on different half-waves of the secondary voltage of the transformer.

Inverter welding source, made according to the topology shown in Fig. 5, allows providing an increased output voltage at no-load and low-load currents, which facilitates the process of ignition of the arc.

4. 4. Experimental verification of a power supply with a full-bridge converter

Using the described technical solutions, an experimental welding power supply with single-phase input was constructed. The full-bridge inverter is made using the transistors VT1 – VT4 of type IRG4PC50UD, controlled by the IRS2113 drivers. The BR1 diode bridge is of type KBJ5010, the diodes VD1 – VD3 are of type 10A10, the thermistor NTC1 – 3D15. The diodes of the main rectifier VD4, VD5 – 150EBU04, additional rectifier VD6, VD7 – 30CPU04 diode pack. The capacitors of the input rectifier C1, C2 – 470 μF × 200 V, the blocking capacitor C3 – 3,3 μF × 400 V. The control system is implemented using a single chip microcontroller STM32F100C8T6B, operating at a clock frequency of 24 MHz.

The block diagram of the welding source control system is shown in Fig. 6. The source operates in the mode of maintaining the specified average load power (signal P*), i. e. the static output V-I characteristic of the supply is hyperbolic within the working range. The task of the control system is the formation the inverter's input current so that it is proportional to the C3 voltage at the time when the diodes VD1, VD3 are reverse-biased.

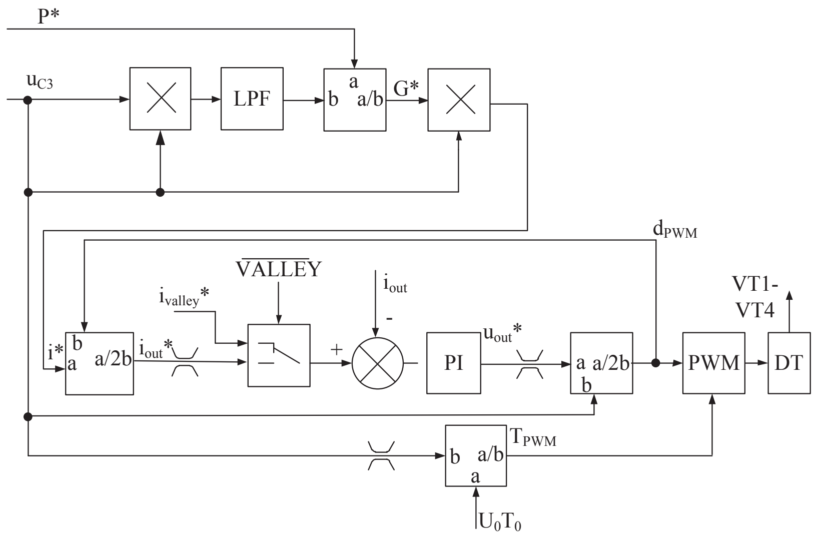

Fig. 6. The block diagram of a control system of the welding source with a full-bridge converter

The signal VALLEY is active when switching to the supply from the bulk capacitors C1, C2 (when the diodes VD1, VD3 are forward-biased). In this case, the output current is maintained at a fixed level i_{valley}*. This is the «sustain» mode of the welding arc.

The measurement of the output current (signal i_{out}) is performed using a current transformer installed in the primary circuit of the power transformer. In this case, the sampling instants of the controller's ADC are synchronized with the PWM carrier frequency. This makes it possible to significantly reduce measurement errors caused by the ripple of the primary winding current at the PWM switching frequency.

To maximize the use of a power transformer, the switching frequency of the full-bridge power switches is made variable and proportional to the voltage at the output of the diode bridge. This allows (to some extent) stabilizing the amplitude of the magnetic flux in the transformer, reducing power losses in the inverter and increasing the stiffness of the output characteristic of the transformer.

In the control system, the PWM period is represented by the T_{PWM} signal, which is proportional to the voltage across the capacitor C3.

As it was said before, the static output V-I characteristic of the described power supply in the working region is hyperbolic (with constant power). This leads to stabilization of the thermal power of the arc and its melting ability; naturally, the forcing of the arc is realized (increase of current with decreasing voltage, «Arc Force» function). Software anti-sticking function is also implemented (current reduction in case of short-circuiting of the electrode to the workpiece, «Anti-Stick» function).

Thus, the developed power supply topology solution allows for providing an increased output voltage of the inverter welding supply at no-load and low-load currents, which facilitates the arc ignition process during welding. However, the transformer ratio of the power transformer for the main rectifier remains unchanged, and the primary current increases insignificantly. This avoids increasing the current load on the inverter, which makes it possible to increase the specific power and increase the efficiency of the supply. In addition, the implementation of the input rectifier using the Valley-Fill scheme can significantly increase the PF of the power supplies built using the proposed scheme. A distinctive feature of the developed power supply is also that the increase in PF is achieved without the introduction of additional power semiconductor components, as well as inductive power components.

5. Results of studies of welding sources with a forward and full-bridge converter

As a result of testing an experimental supply with a forward converter, its PF was calculated, which was more than 0.94 in a wide range of output power variation. Due to this, the RMS current drawn from the mains is 30 to 45 % lower than for conventional inverter supplies without PFC. Fig. 7 shows the oscillograms of the mains voltage and the input current of the experimental power supply with the load power of 1 kW. Fig. 8 shows the oscillograms in the output current limiting mode. Even in this case, the power supply PF remains not less than 0.9.

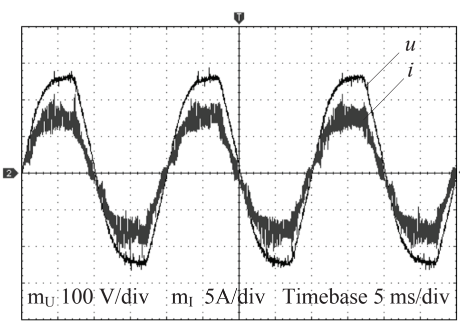

Fig. 7. Oscillograms of the mains voltage (100 V/div) and the input current of the experimental power supply (5 A/div), normal mode. Timebase is 5 ms/div

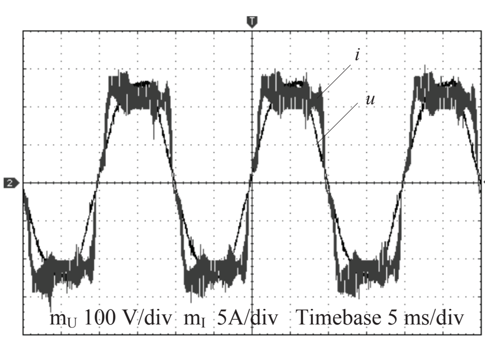

Fig. 8. Oscillograms of the mains voltage (100 V/div) and the input current of the experimental power supply (5 A/div), current limiting mode. Timebase is 5 ms/div

In the experimental welding power supply, the «anti-stick» function is also realized, i. e., the output current decreases with a small output voltage (i. e., when the welding electrode shorts to the workpiece). The measurement of the output voltage is carried out indirectly, by software evaluation of the duration of the magnetization interval, the mains voltage and the voltage across the capacitor C3. This approach eliminates the need to introduce additional components into the power supply circuit.

Also, the software reduces the no-load voltage of the supply during idle time, which increases the safety of welding operations.

The tests of the full-bridge inverter supply, carried out with the use of measuring equipment [17], have shown that its PF changes from 0.94 (at a load power of 0.7 kW) to 0.97 (1.8 kW). In this case, the THD of the input current varies from 32 % (0.7 kW) to 22 % (1.8 kW). Fig. 9 shows the oscillograms of the mains voltage and the input current of the developed power supply at a load power of 1.8 kW. For convenience, the signals in Fig. 9 are normalized to the amplitude.

Fig. 9. The input voltage and input current waveforms of the welding source with a full-bridge converter

Reduction of PF in comparison with the theoretical is due to the presence of bulk capacitors C1, C2 and blocking capacitor C3 recharging pulses (Fig. 5). The second reason for reducing the power supply PF is the accuracy and speed of the current controller in the control system.

6. Discussion of the developed power supplies tests results

The presented circuit topology solutions make it possible to create welding sources that are comparable in parameters with professional-grade inverters (equipped with a PFC), but with a significantly lower cost and better mass-dimensional characteristics. Such welding sources make it possible to ensure the quality of welded joints no worse than the widely used welding inverters for manual DC arc welding, which was confirmed by laboratory tests.

At the same time, the use of sources with increased PF can reduce losses in the electric mains and improve the electric power quality, thus improving the working conditions of other equipment that feeds from these mains. This is due to the decrease in the distortion of the waveshape of the current drawn from the mains. Since the welding sources with high PF have smaller current consumption (lower by 30–40 %) in comparison with widespread welding inverters, this makes it possible to ensure simultaneous operation of a greater number of power supplies with the same apparent power drawn from distribution mains. In addition, the use of such power welding sources makes it possible to ensure their stable operation in the construction site conditions with a considerable length of the input power cable. The aforementioned allows increasing the productivity of welding operations and ensuring the high quality of welded joints.

A further area of research is the improvement of circuitry and control algorithms for converters in order to implement various welding processes (MIG and pulse welding, welding in a CO_2 environment, etc.).

7. Conclusions

1. The original circuit topologies of inverter welding sources based on the forward and full-bridge converters have been developed. The welding sources have the ability to control the input current and have galvanically isolated output due to the use of a high-frequency transformer. The developed welding sources are characterized by a reduced capacity of the DC-link bulk capacitor, and also have an increased and stabilized no-load voltage. These features make it possible to effectively use power supplies to solve the problems of electric arc welding.

2. Algorithms for controlling the developed inverter welding sources providing direct control of their input current are proposed, which makes it possible to increase the PF of the supplies to at least 0.9 (compared to 0.5–0.7 for conventional widespread welding inverters without PFC). At the same time, the algorithms allow controlling the output power of the welding sources effectively and providing a given type of output V-I characteristic.

3. In the proposed converter control software, the following auxiliary functions are implemented: limitation of the open-circuit voltage, the reduction of the output short-circuit current, the output power stabilization (the output current increases with a decrease in the output voltage).

References

1. Korotynsky, A. E. State-of-the-art, tendencies and prospects of development of high-frequency welding converters (Review) [Text] / A. E. Korotynsky // The Paton Welding Journal. – 2002. – Issue 7. – P. 50–62.
2. Pentegov, I. V. Elektromagnitnaya sovmestimost' istochnikov pitaniya svarochnoy dugi [Text] / I. V. Pentegov, S. V. Rymar, A. M. Zhernosekov, V. N. Sydorets // Elektrotekhnika y Elektromekhanika. – 2012. – Issue 3. – P. 34–40.
3. Rymar, S. V. Influence of Welding Power Sources on Three-Phase Mains [Text] / S. V. Rymar, A. M. Zhernosekov, V. N. Sydorets // The Paton Welding Journal. – 2011. – Issue 10. – P. 49–55.
4. Zaruba, I. I. Puti povysheniya tekhnologicheskoy effektivnosti vypryamiteley dlya mekhanizirovannoy svarki i naplavki (obzor) [Text] / I. I. Zaruba, V. V. Andreyev, V. I. Stepakhno, V. A. Koritskiy // Avtomaticheskaya svarka. – 2011. – Issue 11. – P. 45–49.
5. Lebedev, A. V. Transistor Power Sources for Electric Arc Welding (Review) [Text] / A. V. Lebedev // The Paton Welding Journal. – 2012. – Issue 9. – P. 34–40.
6. Galperin, V. Obespecheniye elektromagnitnoy sovmestimosti promyshlennogo tekhnologicheskogo oborudovaniya [Text] / V. Galperin, D. Kolesnik // Elektrooborudovaniye i remont. – 2008. – Issue 7. – P. 8–12.
7. Narula, S. Power Factor Corrected Welding Power Supply Using Modified Zeta Converter [Text] / S. Narula, B. Singh, G. Bhuvaneswari // IEEE Journal of Emerging and Selected Topics in Power Electronics. – 2016. – Vol. 4, Issue 2. – P. 617–625. doi: 10.1109/jestpe.2015.2500610
8. Narula, S. Bridgeless Single-Ended Primary Inductance Converter with improved power quality for welding power supplies [Text] / S. Narula, B. Singh, G. Bhuvaneswari // 2014 IEEE 6th India International Conference on Power Electronics (IICPE). – 2014. doi: 10.1109/iicpe.2014.7115808
9. Mishima, T. A novel bridgeless boost half-bridge ZVS-PWM single-stage utility frequency AC-high frequency ac resonant converter for domestic induction heaters [Text] / T. Mishima, Y. Nakagawa, M. Nakaoka // 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 – ECCE ASIA). – 2014. doi: 10.1109/ipec.2014.6869946
10. Narula, S. Improved Power-Quality-Based Welding Power Supply With Overcurrent Handling Capability [Text] / S. Narula, B. Singh, G. Bhuvaneswari // IEEE Transactions on Power Electronics. – 2016. – Vol. 31, Issue 4. – P. 2850–2859. doi: 10.1109/tpel.2015.2454994
11. Leibl, M. New boundary mode sinusoidal input current control of the VIENNA rectifier [Text] / M. Leibl, M. Darani, J. W. Kolar, J. Deuringer // 2015 IEEE Energy Conversion Congress and Exposition (ECCE). – 2015. doi: 10.1109/ecce.2015.7309689
12. Rozanov, Yu. K. Poluprovodnikovyye preobrazovateli so zvenom povyshennoy chastoty [Text] / Yu. K. Rozanov. – Moscow: Energoatomizdat, 1987. – 183.
13. Galvery, W. L. Welding essentials: questions & answers [Text] / W. L. Galvery, F. M. Marlow. – Industrial Press, 2006. – 469 p.
14. Potapevsky, A. G. Svarka staley v zashchitnykh gazakh plavyashchimsya elektrodom. Tekhnika i tekhnologiya budushchego [Text]: monografiya / A. G. Potapevsky, Yu. N. Sarayev, D. A. Chinakhov. – Tomsk: PH Tomsk Polytechnic University, 2012. – 208 p.
15. Horvath, M. Welding equipment with power factor correction [Text] / M. Horvath, J. Borka // Proceedings of PEMC`96 Conf. Budapest, Hungary. – 1996. – Vol. 2/3. – P. 181–186.
16. Pat. No. US 8581147 B2. Three stage power source for electric ARC welding [Text] / Kooken T. E., Luo L. – No. US 11/087,179; declareted: 24.03.2005; published: 12.11.2013.
17. Burlaka, V. V. Laboratornyy kompleks dlya issledovaniya chastotnykh kharakteristik tsepey [Text]: nauch.-prakt. konf. / V. V. Burlaka, S. N. Kravchuk, S. V. Gulakov, V. V. Leonov // Donbas-2020: Perspektyvy rozvytku ochyma molodykh vchenykh. – Donetsk: DonNTU, 2014. – P. 76–80.
18. Ivanov, V. Improving the Efficiency of Strip Cladding by the Control of Electrode Metal Transfer [Text] / V. Ivanov, E. Lavrova // Applied Mechanics and Materials. – 2014. – Vol. 682. – P. 266–269. doi: 10.4028/www.scientific.net/amm.682.266