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HIGHER CURRENT HARMONICS IN TRANSFORMER POWER SOURCES WITH PULSED DEVICES OF WELDING ARC STABILIZATION

A.M. Zhernosekov[1], **O.A. Andrianov**[2], **S.V. Rymar**[1], **O.F. Shatan**[1], **A.O. Mukha**[1]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]Ukrainian National Committee of International Chamber of Commerce (ICC Ukraine)
19B Reitarska Str. 01034, Kyiv, Ukraine

ABSTRACT

Transformer power sources of welding arc of industrial frequency alternating current generate into the mains the level of higher current harmonics, which is by an order of magnitude lower by the value of the coefficient of general harmonic distortion, than that of the inverter power sources. Here, their high electromagnetic compatibility with other equipment of the mains is achieved. Moreover, they are much easier to maintain and more reliable. Harmonic composition of current during AC welding was calculated at application of pulsed devices of arc stabilization. It is shown that application of stabilizing pulses with the polarity opposite to that of arc current, is more advantageous that the use of pulses with the polarity coinciding with that of arc current. Advantages as to welding process effectiveness and smaller generation of higher current harmonics are also observed.

KEYWORDS: welding power sources, transformers, welding arc, stabilizing pulses, higher current harmonics

INTRODUCTION

Over the last decades great success has been achieved in development and wide introduction of inverter-type welding arc power sources with digital systems of control and regulation of welding current curve shape. However, application of the welding arc of industrial frequency alternating current is still is demand [1–3]. Alternating current arc is supplied from traditional welding power sources, in which the welding transformer is the main power electromagnetic component. Such modern power sources, fitted with additional block of control of the welding arc and impact on it are widely used in industry.

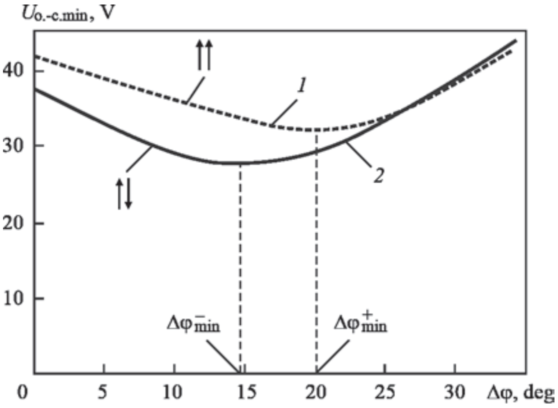

Figure 1. Dependencies of minimal open-circuit voltage of the welding transformer, at which the arc burns, on the difference of phase shift between the welding current and stabilizing pulse: *1* — stabilizing pulse polarity coincides with welding current polarity; *2* — stabilizing pulse polarity is opposite to welding current polarity [3, 6]

Use of pulsed stabilization devices (SD) of arc burning, combined with the traditional AC power sources is a promising direction of applying pulsed impact in AC welding [4, 5]. Application of these devices allows lowering the transformer open-circuit voltage and reducing the consumption of their active materials.

So far there is no single solution on the nature of stabilizing pulse parameters, such as pulse energy, its feeding (injection) time as to the moment of welding current zero crossing, and current polarity. This problem was partially formulated and solved in works [3, 6]. The optimization criterion was selected to be the minimum of power source open-circuit voltage, at which the arc is still stable, and the phase shift difference between the welding current and the stabilizing pulse was the variable parameter. Figure 1 shows the determined dependencies of welding transformer minimal open-circuit voltage, at which the arc is burning, on the difference in phase shift between the welding current and the stabilizing pulse, when the stabilizing pulse polarity coincides with the welding current polarity and it is opposite to welding current polarity. Analysis of the derived curves shows that the dependencies have pronounced minima, and the optimization problem can be solved. One can also see that application of stabilizing pulses of polarity opposite to arc current polarity has an advantage, as the curve of minimum open-circuit voltage $U_{o.-c\ min}$ in this case is located lower than at application of pulses of polarity coinciding with that of the welding current. The following explanation of this fact is given: the stabilizing pulse is directed opposite to the welding current, it does not interfere with the power source operation and promotes the power source operating as a stabilizing device after the pulse is over.

STATEMENT OF THE RESEARCH PROBLEM

Inverter sources for arc welding have flexible adjustment parameters, and open up wide prospects for their application. However, as shown by experience of industrial application of electric welding equipment, the traditional power sources based on welding transformers still remain in demand [1, 4]. This is attributed, primarily to the reliability of their main power electromagnetic component — the transformer, and to the fact that inverter sources generate a considerable level of higher current harmonics into the mains, have low electromagnetic compatibility [7] and are not as reliable. The traditional power sources generate a much smaller harmonic spectrum into the mains [7, 8]. Moreover, the traditional equipment of AC welding arc is much easier to maintain than the welding inverter power sources, which often supply DC current to the arc. In DC welding the interaction of the arc own magnetic field and the welding circuit field deflects the arc due to magnetic blowing, having extremely negative consequences.

However, the questions of higher current harmonics generation by the traditional AC welding power sources fitted with arc stabilization devices, are still insufficiently studied. Investigations described in this paper address this issue.

The objective of this work is calculation of the current harmonic composition during AC welding by traditional transformer power sources at application of pulsed devices of arc stabilization and analysis of higher current harmonic generation by them.

INVESTIGATION RESULTS

Improvement of the traditional welding power sources follows the path of reduction of welding transformer weight. In these sources stable arc ignition, its burning and welding process stability are associated with high levels of open-circuit voltage. If this is ensured by welding transformer voltage, it leads to an essential increase of its weight. At PWI this problem was solved, in particular, by application of voltage multipliers [9], or arc stabilization devices [10, 11], which allow lowering the transformer secondary voltage.

Investigations of the influence of circuit design solution and regulation methods on external characteristics of the traditional transformer power sources, analysis of the influence of these characteristics on the stability of welding arc burning, as well as investigations of the dynamic processes in AC electric circuits at application of stabilizing pulses is rather fully described in works [3, 6, 12]. Let us focus here on determination and analysis of the harmonic composition of alternating welding current at different circuit solutions and methods of regulation of the characteristics of the traditional welding arc sources.

PWI has accumulated extensive experience of development of different types of pulsed devices of AC arc stabilization. Application of such devices in practice allows improvement of the quality of weld formation, raising the welding process efficiency, promoting power saving and also using more efficient modes and inexpensive electrode for DC welding [5].

TYPICAL POWER COMPONENTS OF AC WELDING POWER SOURCE WITH A PULSED ARC STABILIZATION DEVICE

When designing the traditional power sources, it is rational to select welding transformers with developed magnetic scattering fields. Welding current regulation can be ensured by the design of welding transformer proper, or it can be performed by electric methods, for instance, application of an additional reactor, switched by electronic keys. The advantage of such an electric regulation method consists in that the welding arc powering by current without zero pauses is provided.

Figure 2 gives the electric circuit of welding power source with thyristor regulation of welding current. The source consists of welding transformer Tr, choke *L*, two back-to-back thyristors VS_1 and VS_2, connected in parallel to it, arc stabilization device (SD), the output of which is connected to arc gap *A*. Welding transformer Tr includes three windings with turn number w_1, w_2, w_3. Secondary winding w_2 is connect-

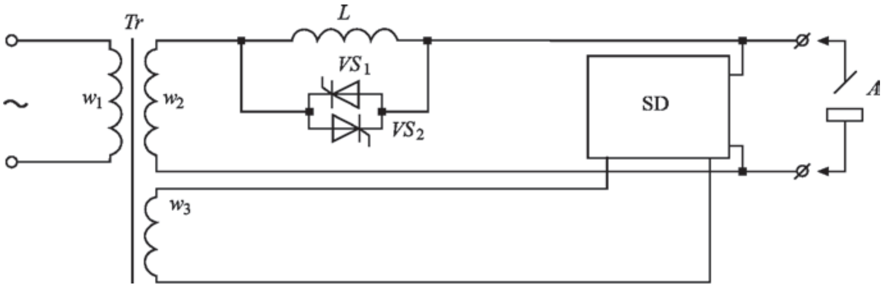

Figure 2. Electric circuit of welding power source with thyristor regulation of welding current

ed in series with choke *L* and welding arc *A*. Winding w_3 powers SD.

Each of thyristors VS_1 and VS_2 is connected with a phase shift by angle ψ relative to voltage on winding with turn number w_2. Regulation of the power source welding current is performed by changing angle ψ. The value of the angle remains unchanged ψ = const during the welding process.

At welding current crossing zero, SD generates a current pulse which is fed to the electric arc facilitating its reignition. SD allows lowering the open-circuit voltage in the secondary winding with turn number w_2 of welding transformer Tr, due to lowering of arc ignition voltage.

INVESTIGATIONS OF ELECTROMAGNETIC PROCESSES IN AC POWER SOURCES WITH THYRISTOR REGULATION

Analysis of transient processes in the power source (Figure 2) at welding arc modeling as anti-EMF with arc voltage U_A, is shown in work [6]. We will use these results to calculate the harmonics spectrum.

Figure 3 [6] shows the oscillogram of arc current, its voltage and open-circuit voltage.

The law of welding current variation at the first stage, taking into account the fact that in the initial phase $\varphi_0 = \varphi$ the initial current is equal to zero, $I_0 = 0$:

$$i_1(t) = \frac{U_m}{\omega(L_s + L)}(\cos\varphi - \cos\omega t) - \frac{U_A}{\omega(L_s + L)}(\omega t - \varphi), \tag{1}$$

where U_m is the amplitude value of voltage in the winding with turn number w_2; ω is the angular frequency; *t* is the time; L_s is the transformer scattering intensity.

From formula (1) not only the law of welding current variation i_1 in the section from φ to ψ, but also the initial effective value of current I_1 for the second switching stage can be determined:

$$I_1 = \frac{U_m}{\omega(L_s + L)}(\cos\varphi - \cos\psi) - \frac{U_A}{\omega(L_s + L)}(\psi - \varphi). \tag{2}$$

The law of welding current variation in the section from ψ up to ψ + α is found from the following expression:

$$i_2(t) = \frac{U_m}{\omega L_s}(\cos\psi - \cos\omega t) - \frac{U_A}{\omega L_s}(\omega t - \psi) + I_1. \tag{3}$$

It is obvious that at the moment of time, when current i_2 becomes equal to I_1, the section with duration $\omega t = \alpha$ ends. Equating the expression for current i_2 at moment of time ψ + α to value I_1 (formulas (2) and (3)), we obtain an equation for determination of switching duration α

$$\frac{U_A}{U_m}\alpha = \cos\psi - \cos(\psi + \alpha). \tag{4}$$

After blanking the respective thyrisor (VS_1 and VS_2), starting from moment of time ψ + α, the law of welding current variation is described by the following expression

$$i_3(t) = \frac{U_m}{\omega(L_s + L)}\left[\cos(\psi + \alpha) - \cos\omega t\right] - \frac{U_A}{\omega(L_s + L)}\left[\omega t - (\alpha + \psi)\right] + I_1. \tag{5}$$

One can see that the right sides of formulas (1) and (5) are identical, so we will use the latter to facilitate further calculations.

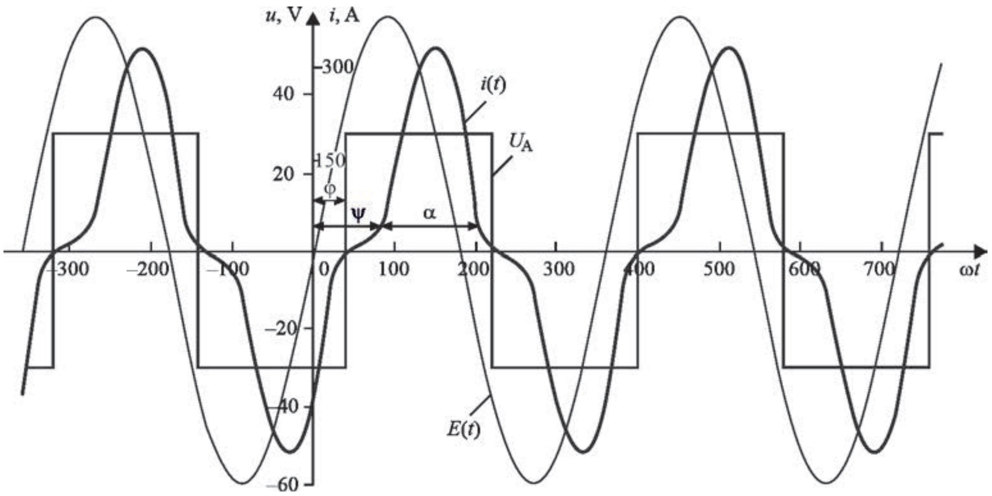

Figure 3. Time dependencies of arc current I_A, arc voltage U_A and open-circuit voltage *E*

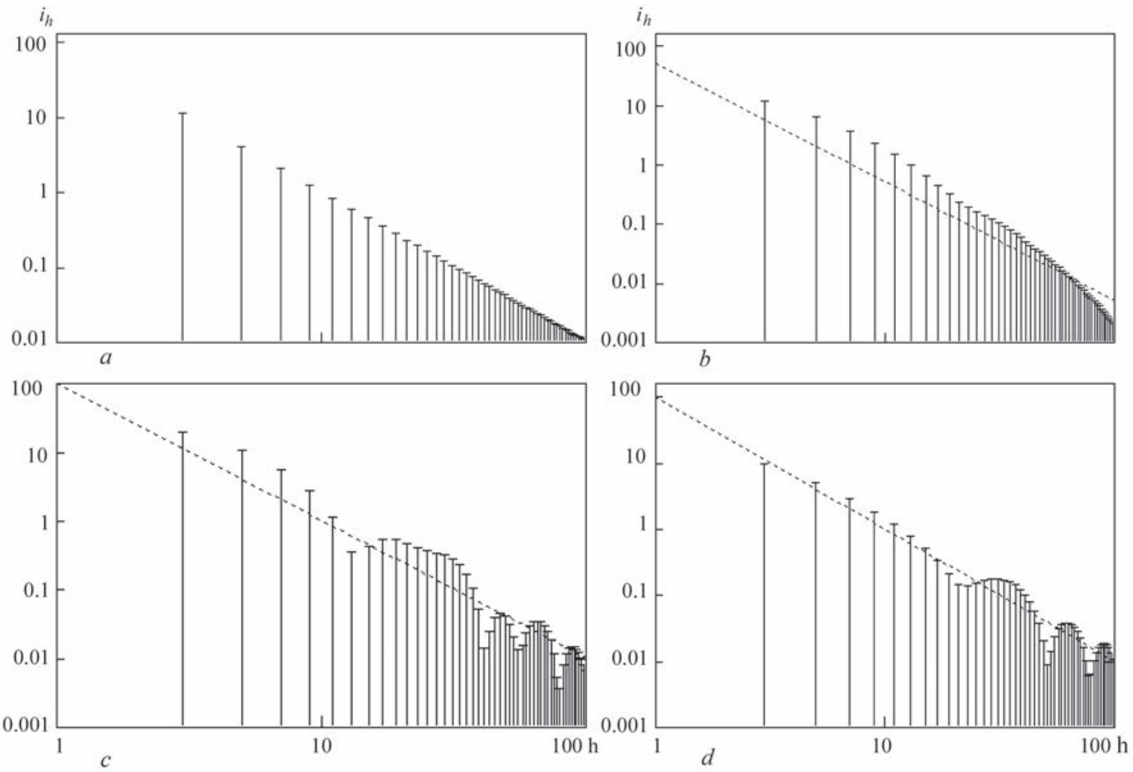

Figure 4. Harmonics composition of welding current $|i_h|$ at arc powering by AC: arc as anti-EMF (*a*): dynamic model of welding arc (*b*); arc with stabilizing pulses, when pulse polarity coincides with arc current polarity (*c*); pulse polarity is opposite to arc current polarity (*d*): *a* — THD_i = 9.1 %; *b* — 9.2; *c* — 15.7; *d* — 7.4

Knowing currents i_1, i_2, i_3, as well as the time intervals of their flowing and setting the angle of switching of thyristors VS_1 and VS_2, we will determine the expression for welding current in the half-period:

$$i(t) = \begin{cases} i_1(t), & \varphi < \omega t < \psi; \\ i_2(t), & \psi < \omega t < \psi + \alpha; \\ i_1(t), & \psi + \alpha < \omega t < \pi. \end{cases} \quad (6)$$

Having determined the time dependencies of currents at three commutation stages (Figure 3), we can find the harmonics composition of welding current:

$$i(t) = \sum_{h}^{\infty} \left[a_h \cos(h\omega t) + b_h \sin(h\omega t) \right], \quad (7)$$

where h is the harmonic number; coefficients

$$a_h = \left[1 + (-1)^h \right] \frac{\omega}{\pi} \int_0^{\frac{\pi}{\omega}} i(t) \cos(h\omega t)\, dt;$$
$$b_h = \left[1 + (-1)^h \right] \frac{\omega}{\pi} \int_0^{\frac{\pi}{\omega}} i(t) \sin(h\omega t)\, dt, \quad (8)$$

and current module

$$|i_h| = \sqrt{a_h^2 + b_h^2}. \quad (9)$$

Figure 4 shows the harmonics composition of welding current $[i_h]$ at arc powering by alternating current (arc as anti-EMF). One can see from the figure that even current harmonics are absent.

The coefficient of Total Harmonics Current Distortion (THD) [13] is found by the following formula:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{\infty} |i_h|^2}}{|i_1|}. \quad (10)$$

The result coincides with harmonics balance method earlier obtained in work [14].

ANALYSIS OF AC ARC STABILITY AND MODELING ITS DYNAMICS

We will study the influence of stabilizing pulses on the welding arc. A peculiarity of this study, based on mathematical modeling method, consists in selection of the dynamic model of the welding arc. The welding arc model in the form of anti-EMF used above for studying the dynamic processes in electric circuits with an arc is unsuitable, as it is essentially static.

The generalized mathematical model of a dynamic arc [15, 16] developed at PWI, provides the most adequate description of electric arc dynamics as an electric circuit element. It takes into account not only the nonlinearity of volt-ampere characteristic, but also the thermal inertia of the arc column. These are exactly the thermal processes, and, primarily, the ionization-deionization process, which affect the con-

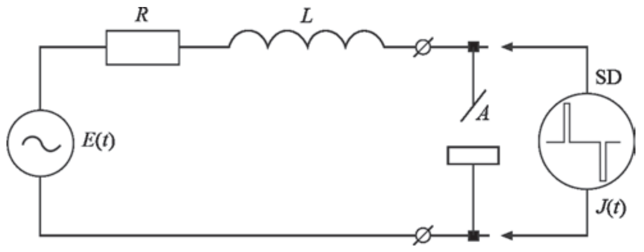

Figure 5. Simplified scheme of power components of the traditional AC welding power sources

ductivity of arc column plasma. The column of 50 Hz AC arc has enough time to deionise at each change of polarity that requires higher voltage to maintain the discharge. If the power source cannot provide the required voltage, the arc is extinguished.

Let us consider an electric circuit (without connection of a pulsed stabilizer) which is shown in Figure 5, and which is a simplified schematic of the power part of traditional AC welding sources connected to arc *A*. A system of differential equations describing this circuit, consists of Kirchhoff's equation and equation of the generalized mathematical model of a dynamic arc

$$L\frac{di}{dt}+Ri+u_A=E\left(t\right);\,\theta\frac{di_\theta^2}{dt}+i_\theta^2=i_A^2, \qquad (11)$$

where *i* is the current of reactor *L* and resistor *R*; *E*(*t*) is the power source voltage, having the form of $E(t) = U_m \sin(\omega t - \varphi)$ in the general case; U_m is the open-circuit voltage amplitude; φ is the phase shift angle; i_θ is the current of the arc static state; θ is the characteristic time (time constant of the arc); i_A is the arc current.

In order to find the harmonics composition of the welding current, we will use the results of work [6] and sequence of actions to solve the system of equations (1).

Figure 6, *a* [6] presents modeling results, from which one can see that the shape of arc voltage has pronounced ignition peaks in each half-wave, which exceed the arc voltage. Increased voltage is ensured both by presence of inductance and by phase shifting between arc current and power source voltage.

Knowing the time dependencies of current, we can determine its harmonics composition (see Figure 4, *b*). Although this harmonics composition is different from the spectrum obtained at arc modeling as anti-EMF (compared to Figure 4, *a*) THD_i distortion coefficient practically does not differ.

One of the variants of arc stabilization by current pulses fed from an additional power source, is shown in Figure 5 with connected SD pulsed current source. The system of differential equations which describes transient processes at the pulse stage, follows from system (11), if arc current [3, 6].

$$i_A = i + J(t) = i + J_\mathrm{m} \sin \Omega t, \qquad (12)$$

where J_m and Ω are the amplitude and frequency of current pulses.

As one can see from Figure 6, *b* [6] additional pulses lower the arc voltage, which almost does not change during the AC half-wave.

The system stability can be studied, when changing the parameters of the current pulses and the parameters of the main power source. The computer software packages include procedures for integration of systems of regular differential equations. These procedures, however, ensure continuous integration and they are not suitable for integrating systems, where the right parts are different in different time intervals. Their direct application is impossible. Their upgrading, modification and adaptation for this class of problems are required. We will describe a procedure, which was used in these studies.

There is a modified method of shooting and method of multiple shooting to derive periodic solutions in autonomous electric circuits with an arc [17], which can be applied for nonautonomous circuits with an arc. Operation experience [6] showed that reduction of the Cauchy problem to a boundary value problem

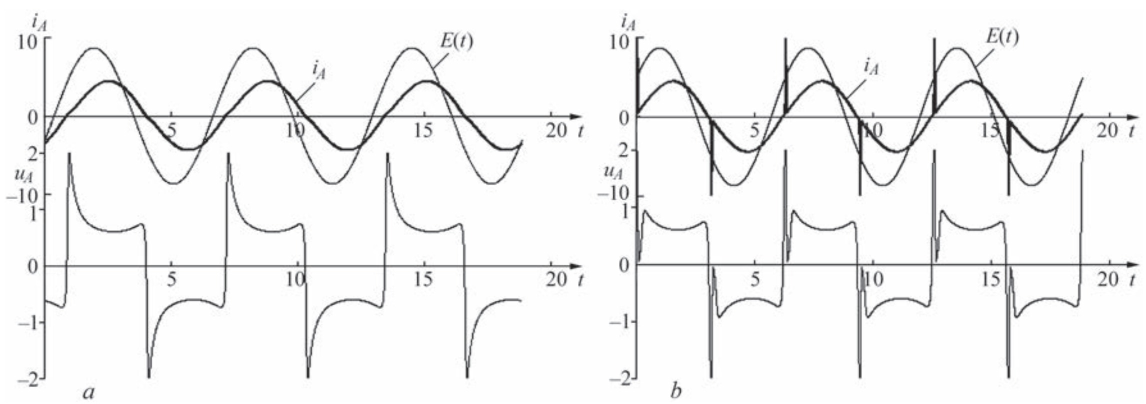

Figure 6. Time dependencies of arc current i_A, arc voltage U_A and open-circuit voltage *E* obtained as a result of modeling: *a* — without current pulses; *b* — with current pulses

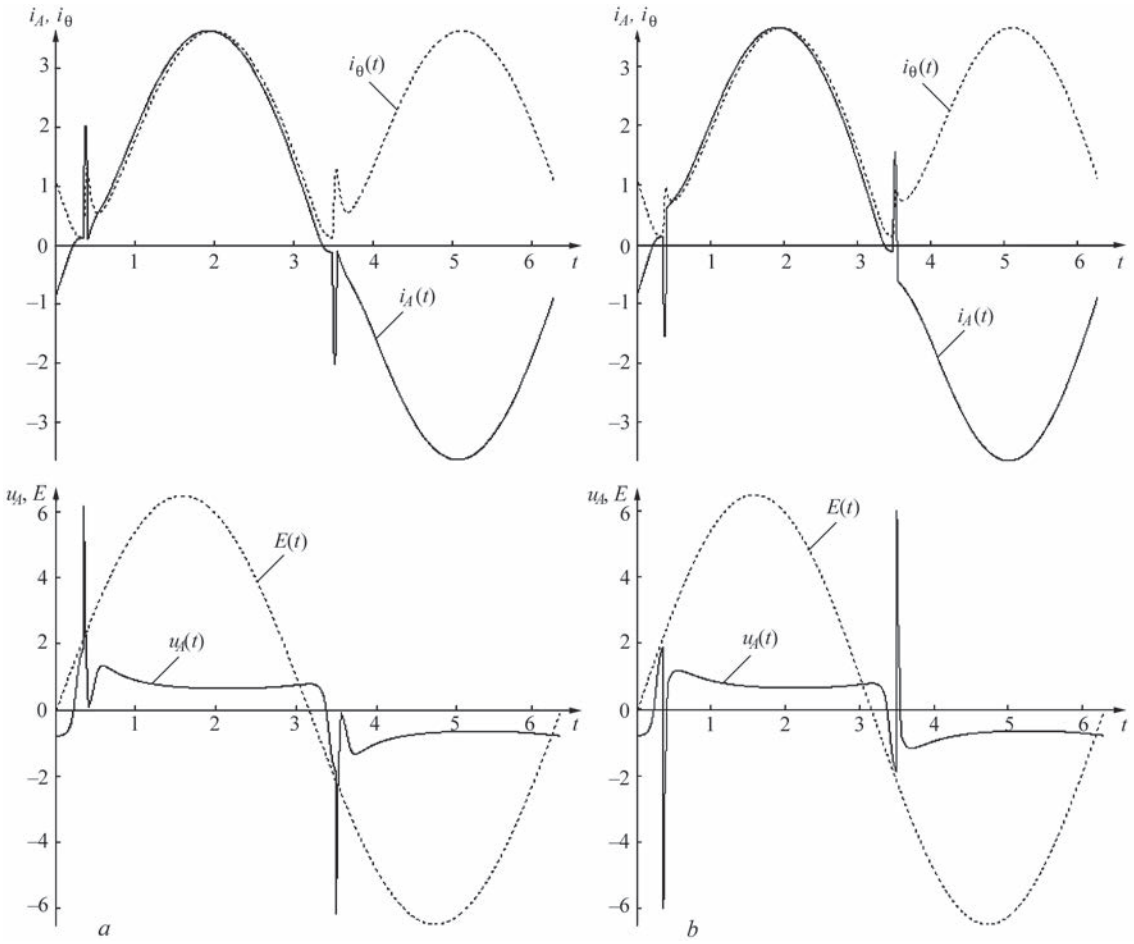

Figure 7. Time dependencies of currents and voltages in a power source with stabilizing pulses: pulse polarity coincides with arc current polarity (*a*); pulse polarity is opposite to arc current polarity (*b*)

with the conditions of half-wave matching at the level of I and I_θ

$$i\left(0,\frac{\pi}{\omega},I,I_\theta\right)=-I;\ \theta\frac{di_\theta^2}{dt}+i_\theta^2=i_A^2, \qquad (13)$$

is unjustifiably cumbersome and requires powerful computing devices (here, $i(t_0, t, I, I_\theta)$ and $i_\theta(t_0, t, I, I_\theta)$ are formal designation of the solution of the system studied by us). This is explained by the need for an additional solution of the variation problem.

Some computer math packages, for instance, MathCAD, allow formally writing the conditions of matching in the half-wave and solving these equations without involving the variational methods. The matching solutions at zero current have the following form:

$$i\left(\varphi,\frac{\pi}{\omega},0,I_\theta\right)=0;\left(\varphi,\frac{\pi}{\omega},0,I_\theta\right)=I_\theta. \qquad (14)$$

here, I_θ and φ are the unknowns to be determined.

This is exactly the path, which is promising due to its simplicity at application of its results for harmonics analysis.

HARMONICS ANALYSIS OF STABILIZATION MODES

Figure 7 shows time dependencies of currents and voltage in the power source with stabilizing pulses [3, 6], derived by the above-given formulas, which coincide quite well with experimentally obtained oscillograms [5]. Figure 7, *a* presents a case when the pulse polarity coincides with arc current polarity, and Figure 7, *b* — when pulse polarity is opposite to arc current polarity.

These time dependencies of current were used to derive by formulas (8) and (9) its harmonics composition, shown in Figure 4, *c*, *d*. Figure 4, *c* gives the harmonics composition of current in the power source with stabilizing pulses, when the pulse polarity coincides with that of arc current, and Fig, *d* shows the case when pulse polarity is opposite to that of arc current.

As was mentioned above, the best is the mode, when the stabilizing pulse polarity is opposite to that of welding current [3, 6]. Its technological effectiveness is confirmed in work [18]. Comparison of Figure 4, *a*, *b*, *d* demonstrates that application of such a mode is more promising also in terms of electromagnetic compatibility. The level of higher harmonics with THD_i = 7.4 % is lower than of those with THD_i = = 9.1 and 9.2 % for power sources without welding arc stabilizers.

CONCLUSIONS

1. One of the promising directions of application of pulsed impact in AC welding is use of pulsed devices of arc stabilization in combination with AC transformer power sources.

2. Application of stabilizing pulses with polarity opposite to that of arc current prevails. Here, it is possible to obtain minimum weight and size parameters of the power source and achieve high electromagnetic compatibility due to a low level of higher harmonics generated into the mains.

3. Obtained value of the total coefficient of nonlinear distortions of current is lower than the existing standards for power quality. It opens up a prospect for upgrading the currently available and development of new competitive power sources based on welding transformers with pulsed stabilization of the welding arc.

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ORCID

A.M. Zhernosekov: 0000-0002-6404-2221,
O.A. Andrianov: 0000-0003-4767-3205,
S.V. Rymar: 0000-0003-0490-4608,
O.F. Shatan: 0000-0001-6553-7421,
A.O. Mukha: 0000-0001-9810-4569

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

A.M. Zhernosekov
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: zhernosekov@paton.kiev.ua

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