EFFECT OF SINGLE-PHASE POWER SOURCES OF WELDING ARC ON ELECTRIC MAINS

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Harmonic composition of the electric mains in operation of single-phase welding power sources was investigated. It is shown that the welding power sources generate the higher harmonics of current into mains, in particular triplen harmonics, thus deteriorating the quality of electric power. It is recommended to apply the filters of higher harmonics for decreasing the effect of single-phase welding power sources on electric mains.

Keywords: *electric mains, single-phase welding power sources, higher harmonics of current and voltage, coefficient of non-linear distortions of current and voltage*

At the end of the XX century the industrialized countries encountered the problem of growing deterioration of quality of electric power in mains, consisting in distortion of a sinusoidal shape of mains current and voltage, that caused the increase in losses and decrease in safety of electric equipment service. This resulted in growing of amount of equipment with non-linear loads, generating of higher harmonics of current into electric mains.

Single-phase non-linear loads (pulsed power sources, adjustable-frequency electric drives, rectifiers and inverters, systems of automatic control, computer systems of technological process control, TV equipment, office equipment, energy-saving lamps, etc.) lead due to their large quantity to increase in value of coefficient of total non-linear (harmonics) current distortion [1] up to THD_I of 90–140 %, especially due to generation of a zero sequence (the 3rd one and harmonics, multiple by it up to 80 %) [2].

Single-phase non-linear loads deteriorate electromagnetic compatibility that can lead to non-reliable operation and failure of electric and electron equipment [1, 2], burn-out of lighting devices, corrosion of earthing elements, quick ageing of insulation, overheating of rotors and wear of bearings of electric motors. Due to prevailing of the 3rd harmonic and harmonics, multiple by it, in the mains, the reverse rotation of asynchronous electric motors and burning of insulation of neutral wires up to their ignition at current exceeding in a neutral wire above a design level may occur.

Higher harmonics of current increase also the total value of coefficient of total non-linear (harmonic) voltage distortion of mains up to THD_U of 7 % and higher.

The European and national standard documents, determining the parameters of quality of single-phase mains, do not specify the levels of coefficient of non-linear distortions of current, but limiting the absolute values of current of definite harmonics. In Ukraine the standard is valid only for single-phase mains with current of not more than 16 A per phase [3]. In the North America [4] and EU countries the THD_I levels are standardized for three-phase mains. Therefore, it is possible to predict the appearance of standardized documents, limiting the THD_I levels also in single-phase mains.

The values of coefficient of non-linear distortions of voltage are considered acceptable, which reach 3 % for individual non-linear loads, while the allowable value was defined as 5 % for combined loads of the mains [4]. The national standardized documents [3] allow value of THD_U = 8 %, at which the sinusoidal voltage of mains is already greatly distorted.

To reduce the effect of higher harmonics of current is possible by using the filters of higher harmonics of current, which decrease their level in the mains.

Single-phase welding equipment for electric arc supply, being a non-linear load, welding rectifiers and inverters generate also the powerful higher harmonics of current. Therefore, each year the decrease of level of current harmonics in operation of welding equipment becomes more and more actual. It is especially urgent for promotion of national welding technologies and equipment into industrialized countries.

The aim of the present work is to study the effect of operation of typical single-phase welding power sources on electric mains and issue of recommendations for decreasing the higher harmonics of current, generating by them. The article is the continuation of work [5], in which the welding power sources operating at three-phase electric mains were considered.

Such single-phase power sources for welding arc supply were considered, which were connected to AC mains of 50 Hz frequency, representing the single-phase non-linear loads in the welding manufacturing:

- industrial single-phase welding transformer STSh-250 (transformer for welding current of up to 250 A) with a developed transverse magnetic leakage fluxes and a magnetic shunt, containing a device for stabilization of welding arc burning [6–8]. It is serially manufactured by the Pilot Plant of Welding Equipment of the E.O. Paton Electric Welding Institute and designed for manual arc welding with AC stick electrodes. The presence of device for stabilization of welding arc burning allows also realizing welding with DC electrodes;

- single-phase welding power source VDU-125 with a capacitor voltage multiplier (universal arc rectifier for welding current of up to 125 A). It consists of a welding transformer with developed yoke magnetic leakage fluxes and capacitor voltage multiplier with a bridge diode circuit of rectification [9, 10]. The voltage multiplier provides the improved initial ignition of welding arc, ignition in transition of current through zero and stability of its burning. It was designed and manufactured at the E.O. Paton Electric Welding Institute and also at the Institute of Electrodynamics of the NASU in small batches. The power source has a discrete adjustment of welding current and designed for manual arc welding with AC stick electrodes;
- single-phase welding power source VDU-201 with a capacitor voltage multiplier and thyristor adjustment of welding current (for welding current of up to 200 A). It consists of a welding transformer with yoke magnetic leakage fluxes with a bridge thyristor circuit of rectification, parallel-connected auxiliary diode bridge rectifier and phase-shifting reactor to provide the continuous welding current in operation of thyristors. It was designed at the E.O. Paton Electric Welding Institute and manufactured by the Lithuanian enterprise «Relema» (Vilnius) and designed for manual arc welding with AC and DC stick electrodes;
- industrial single-phase thyristor inverter power source VDI-200, manufactured by the Pilot Plant of Welding Equipment of the E.O. Paton Electric Welding Institute and designed for manual arc welding of low-carbon and alloyed steels with AC and DC stick electrodes.

As a measuring unit, an analyzer of quality of electric mains (single phase) Chauvin Arnoux C.A. 8230 (France) was used, allowing obtaining time dependencies of current and voltage with their typical values (maximum and minimum; full, active and reactive power, etc.), as well as spectra of harmonics up to maximum number of harmonic $h_{\max} = 50$.

Let us consider the operation with mains of welding transformer STSh-250, containing a device for stabilization of welding arc burning.

Figure 1, *a* shows dependencies of relative instantaneous values of current i_* and voltage u_* in mains on time t in operation of welding transformer, obtained in welding of stainless steel 12Kh18N10T with stick electrode OZL-8 of 3 mm diameter at 90 A welding current. Values i_* and u_* refer to their highest amplitude values: $i_* = i/|I_m|$ and $u_* = u/|U_m|$, where $I_m = 80.8$ A, $U_m = -313.2$ V, selected from technical characteristic, where highest «+» and lowest «–» are the amplitude values of voltage and current for periods I_{m+}, I_{m-}, U_{m+}, U_{m-}, obtained during experiment.

Shape of curves of current and voltage is negligibly differed from sinusoidal one. The superposition of a short-time pulse, corresponding to a stabilizer pulse, and also a small bend of current curve during transition through zero were noted.

Figure 1, *b* shows diagram of harmonic components h of current $I_{h\%}$ and voltage $U_{h\%}$ from effective value of current and voltage of the 1st main harmonic, taken as 100 %: $I_{h\%} = I_{h\%}/I_1 \cdot 100$ %, $U_{h\%} = U_{h\%}/U_1 \cdot 100$ %. Values of numbers of harmonics are limited by number 27 for improving the diagram visualization.

It is seen from diagram that during the welding transformer operation the 3rd harmonic of current, equal to 15.3 % of the 1st one, and the 5th, being 2.3 %, are clearly seen in mains, while the rest uneven harmonics of current do not exceed 1 %. Uneven numbers of harmonics of voltage, reaching more than 1 % of the 1st harmonic, have the following values: the 3rd — 2.5, the 5th — 1.3, the 9th — 1 %. There is also a constant component of current of 10.9 % and even harmonics of current (the 2nd — 2.8, the 4th — 2.4 %). The constant component and even harmonics of voltage are negligibly expressed.

Coefficients of non-linear distortions of current and voltage of transformer STSh-250 [1] are $\mathrm{THD}_I =$ $= 15.9$ and $\mathrm{THD}_U = 3.1$ %.

K-factor, determining how much the incremental losses in electric equipment and conductors of electric mains are increased as compared with the fact if only the 1st main harmonic of current was passing in equipment and mains, is equal to 1.38.

Incremental losses are caused by eddy currents, passing in current-carrying parts and conductors of electric mains. The eddy currents themselves are due to magnetic leakage fluxes, passing through the current-carrying parts and conductors.

Thus, the incremental losses in mains and equipment during operation of welding transformer being considered at the given type of its load are increased by 1.38 times. The Table gives the main parameters of operation of the welding transformer at the type of load being considered.

When varying the welding conditions, these values can vary within the range of 13–24 %, and the coefficient THD_U — within 2.5–3.5 %. These results confirm the theoretical analysis of harmonic composition of alternating current of arc [11], which is supplied from the welding transformer.

The welding transformer STSh-250 generates not very high harmonic components of current into supply mains, though they can show negative effect on operation of equipment connected to the mains. Value of THD_U is also not high. The shown characteristics are also typical to other types of single-phase welding transformers.

Main parameters of mains in operation of welding arc power sources

Parameter	STSh-250	VDU-125	VDU-201	VDU-200
I_{m+}, A	80.8	30.2	61.2	59.5
U_{m+}, V	310.6	304.5	312.2	312.9
I_{m-}, A	−74.3	−33.3	−54.7	−59.6
U_{m-}, V	−313.2	−304.3	−315.1	−313.1
I, A	41.0	23.8	26.1	36.8
U, V	221.0	210.6	220.1	221.5
S, V·A	9895.9	5008.3	5202.2	8282.5
P, W	2787.2	3701.6	2543.6	6130.1
Q, var	9495.2	3373.6	4537.9	5569.6
k_P	0.282	0.739	0.489	0.740
cos φ	0.280	0.764	0.530	0.980
tg φ	3.376	0.816	1.573	−0.129
THD_I, %	15.983	16.879	41.165	86.366
THD_U, %	3.110	2.256	3.624	5.957
K	1.383	1.309	3.233	7.259

Notes. 1. Here I, U — effective values of current and voltage; S, P, Q — full, active and reactive (can include distortion power in the presence of harmonics) powers; k_P — coefficient of power, equal to ratio of active and full power P/S; cos φ — coefficient of phase shifting between current and voltage. 2. Formulae for calculation of parameters are given in work [5].

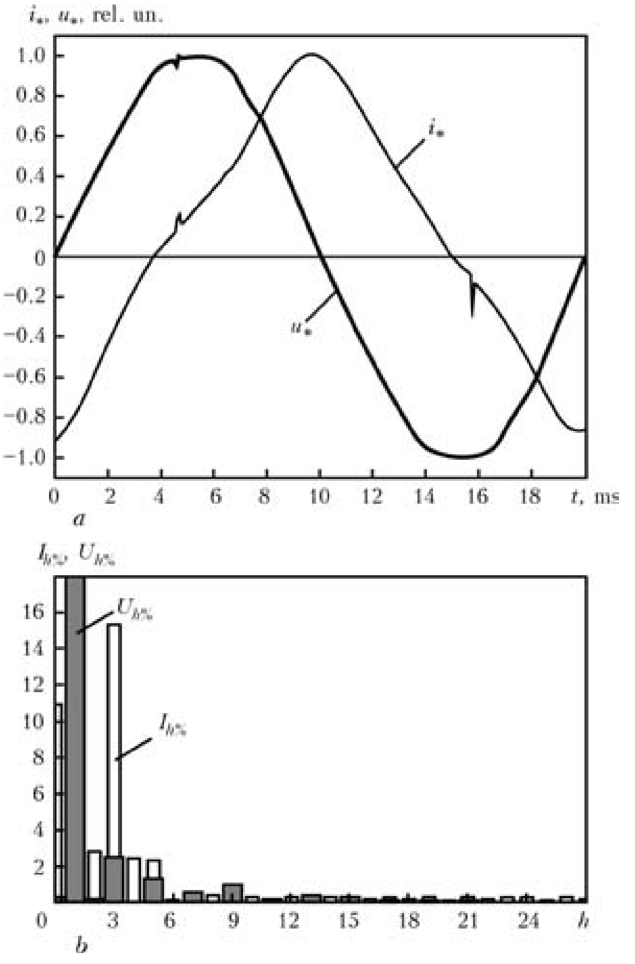

Figure 1. Dependence of current and voltage on time in supply mains of industrial single-phase welding transformer STSh-250 with device for stabilization of welding arc burning (*a*), and harmonic composition of mains current and voltage (*b*)

Figure 2, *a* shows time dependencies of relative values of current and voltage in mains during operation of welding power source VDU-125. Characteristics were recorded during welding with 3 mm diameter stick electrodes ANO-22 at 120 A welding current. The highest amplitude values of current and voltage during experiment were the following: I_m = = −33.3 A, U_m = 304.5 V. After current transition through zero a low disturbance is superposed on sinusoidal current, caused by operation of voltage multiplier. The shape of voltage is very close to sinusoidal.

Figure 2, *b* shows diagram of harmonic components of effective value of current and voltage. It is seen from this diagram that during operation of power source the 3rd harmonic of current, equal to 15.6 % of the 1st harmonic, and the 5th, equal to 4.6 %, are well expressed in supply mains. The rest uneven harmonics of current do not exceed 1 %. The uneven numbers of harmonics of voltage, having more than 1 % of the 1st harmonic, have the following values: the 3rd — 1.6, the 5th — 1.1 %. The constant component of current is equal to 3.7 %. Even harmonics of current are as follows: the 2nd — 4.0, the 4th — 1.1 %. The constant component and even harmonics of voltage are negligibly expressed.

The coefficients are equal to THD_I = 16.9, THD_U = = 2.2 %. *K*-factor reaches 1.31.

Welding power source VDU-125 has acceptable values of THD_I and THD_U. Incremental losses in mains and equipment during operation of power source at the mentioned type of load are 1.3 times increased.

When varying the welding conditions, the values given in the Table, are changed, here THD_I will be 8.7–20.8, THD_U — 2.2–2.8 %.

These characteristics are typical of all types of welding power sources with a capacitor multiplier of voltage, different of types of welding transformers, manufactured as VDU-140, VDU-160 and VDU-180 and designed at the E.O. Paton Electric Welding Institute.

Figure 3, *a* shows time dependencies of relative values of current and voltage in supply mains during operation of welding power source VDU-201. The highest amplitude values of current and voltage are as follows: I_m = 61.2 A, U_m = −315.1 V. Experiments were performed in welding with 3 mm diameter stick electrode ANO-22 at 90 A welding current. A current pulse of high amplitude at commutation of thyristors was superposed on a basic sinusoidal current of low amplitude, which was provided by a phase-shifting reactor. Sinusoid of voltage had only a negligible distortion just after maximum value.

Figure 3, *b* shows harmonic composition of current and voltage at the input of welding power source. In

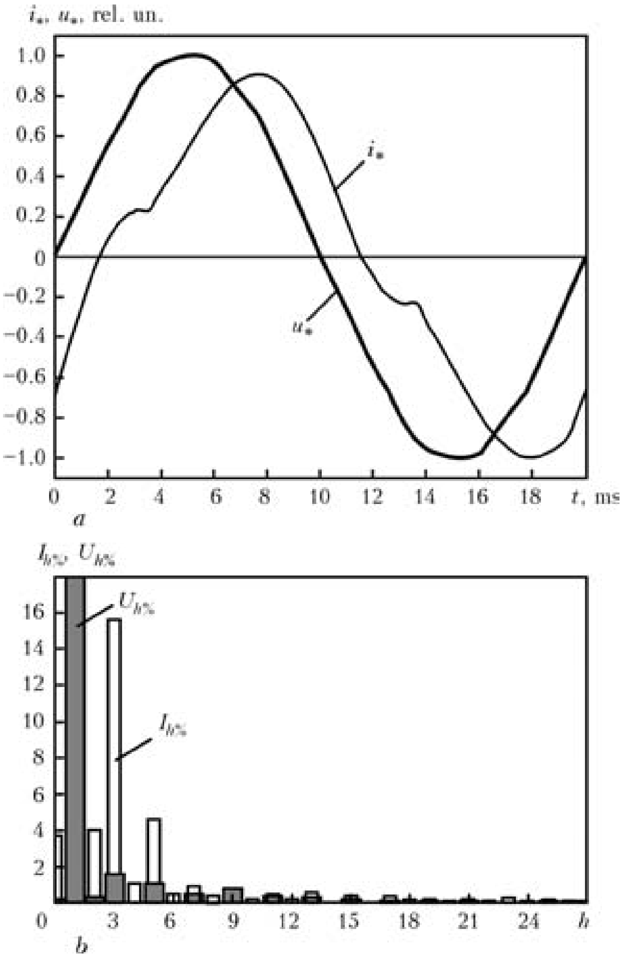

Figure 2. Dependence of current and voltage on time in supply mains of single-phase welding power source VDU-125 with capacitor multiplier of voltage (*a*), and harmonic composition of mains current and voltage (*b*)

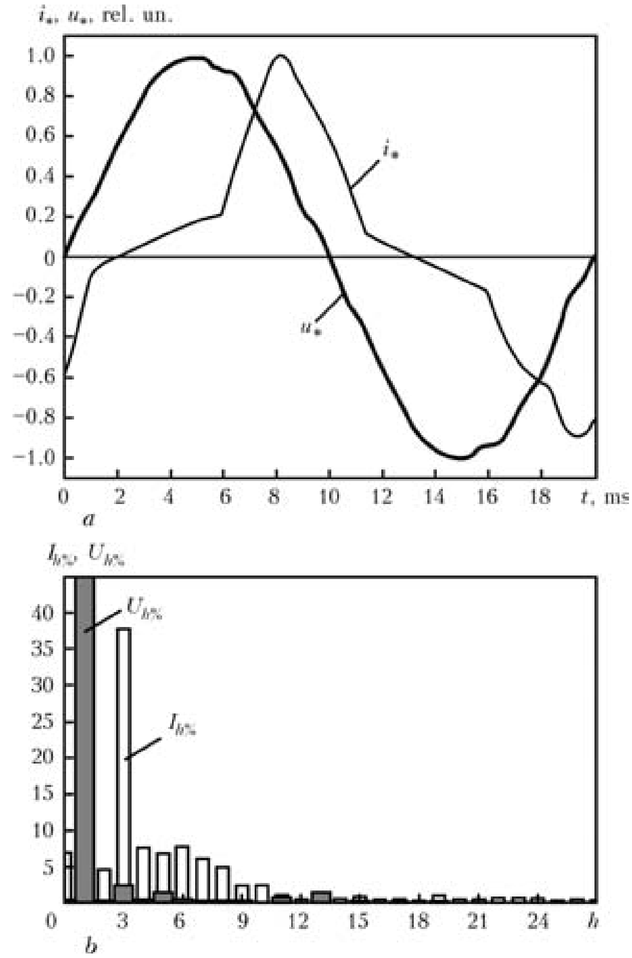

Figure 3. Dependence of current and voltage on time in supply mains of single-phase welding power source VDU-201 with capacitor multiplier of voltage (*a*), and harmonic composition of mains current and voltage (*b*)

the power source mains the 3rd harmonic of current, equal to 37.7 % of the 1st harmonic, the 5th — 6.8, the 7th — 6.1, the 9th — 2.5, the 11th — 1.1, the 13th — 1.0 and 19th — 1.1 % are expressed, the rest uneven harmonics of current did not exceed 1 %. Uneven numbers of harmonics of voltage of more than 1 % of the 1st harmonic had the following values: the 3rd — 2.5, the 5th — 1.6 and the 13th — 1.4 %. Expressed are the constant component of current (6.8 %) and its even harmonics (the 2nd — 4.5, the 4th — 7.7, the 6th — 7.9, the 8th — 5.0 and the 10th — 2.4 %). The constant component and even harmonics of voltage are negligibly expressed.

The coefficients of non-linear distortions of current and voltage of power source VDU-201 have the following values: THD_I = 41.2, THD_U = 3.6 %, K = 3.2. In this power source the value of coefficient THD_I is high. In addition, high harmonic components of current, which are also important, generate into mains.

Incremental losses in mains and equipment during the operation of power source at the mentioned type of load are increased by more than 3 times.

The Table shows main parameters of power source operation at the given type of load. In case of varying the welding condition these values are changed, here the coefficient THD_I will be 9.5–46.5 %, and the coefficient THD_U — 1.8–3.9 %.

Figure 4, *a* shows time dependencies of relative values of current and voltage in mains during operation of welding inverter VDI-200. The highest amplitude values of current and voltage in experiment were equal to I_m = –59.6 A, U_m = –313.1 V.

Figure 4, *b* shows harmonic composition of current in mains line and linear voltage at the input of welding power source during welding of low-alloy steel St3 with 5 mm diameter electrodes UONI-13/55 at 200 A welding current.

In mains of power source almost all uneven harmonics of current are expressed, in particular the 3rd current harmonic, equal to 75.1 % of the 1st harmonic, the 5th — 39.5, the 7th — 10.5, the 9th — 8.3, the 11th — 7.4, the 13th — 1.2, the 15th — 3.1, the 17th — 2.4, the 21st — 1.9, the 27th — 1.1 %. The uneven numbers of harmonics of voltage of more than 1 % of the 1st harmonic have the following values: the 3rd — 5.2, the 5th — 2.2, the 7th — 1.4 %. The constant component of current and voltage is absent. Even harmonics of current are negligibly expressed.

The coefficients of non-linear distortions of current and voltage of power source VDI-200 are as follows: THD_I = 86.4 %, THD_U = 5.9 %, K = 7.2.

The curve of current represents the clearly expressed pulse on the background of almost zero values at the rest extension of a semi-period, the value of coefficient THD_I is rather high for power source VDI-200. Moreover, very wide spectrum of harmonic components of current generates into mains. The curve of voltage, though being like a sinusoid, has cuts in the region of extremums, therefore, the amplitudes of harmonic components of voltage are also high. This shape of curve of voltage can lead to false operation of devices of continuous supply, connected to the same mains, which are connected in case of lowering the amplitude value of mains voltage.

Incremental losses in mains and equipment during operation of power sources at the given type of load are increased by more than 7 times. The Table shows main parameters of operation of power source VDI-200 at the given type of load. Negative value tg φ proves that inverter power source is an active-capacitive load for the mains.

When varying the welding condition these values are changed, here the coefficient THD_I = 82.0–121.5 %, and the coefficient THD_U = 2.8–6.7 %.

By analyzing the given data, it is possible to make a conclusion that to improve the quality of electric power and to reduce the level of higher harmonics of current and voltage, generated by welding equipment, it is rational in a number of cases to apply filters of higher harmonics of current. Here, the welding power sources, except providing the required technological characteristics, will have a good electromagnetic compatibility, and also reduce the incremental losses in mains wires and equipment connected to the mains.

It is necessary to note the positive properties of transformer power sources of arc, which except technological effectiveness, safety and low cost, have a negligible effect on the mains. Welding transformers and power sources, manufactured on their base, provide the adjustment of welding current by transformer itself [12] (without electron unit of current adjustment). This is due to the fact that the welding transformer has an increased leakage inductance to provide a steep-falling external characteristic [12, 13], and this promotes the decrease in higher harmonics of current. The capacitors of voltage multiplier and welding transformer with developed magnetic leakage fluxes form something like an inner filter of higher harmonics of current of power source. However, the higher harmonics of current themselves (in absolute values) are rather high, therefore, the application of filters of higher harmonics is desirable for the single-phase welding transformers and power sources manufactured on their base. In this connection, the transformer power sources of welding arc are characterized, in spite of their increased mass, by many positive properties. They should be also developed and improved in future, for example, together with capacitor multipliers of voltage, which greatly decrease the mass of transformer and consumed power in mains, or with devices of stabilization of welding arc burning, whose application gives an opportunity to use DC electrodes in welding.

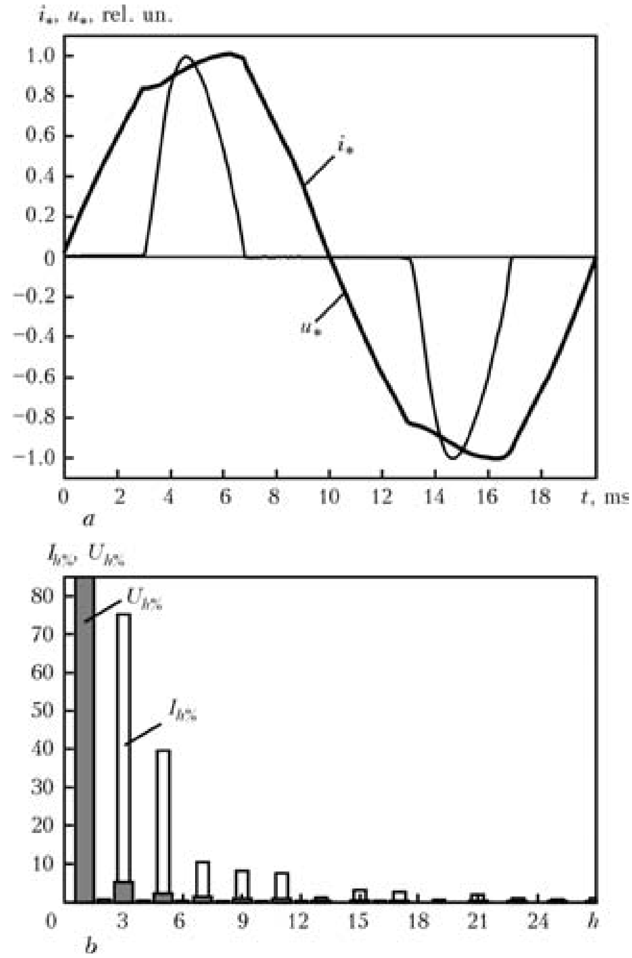

Figure 4. Depence of current and voltage on time in supply mains of single-phase transformer inverter power source VDI-200 (*a*), and harmonic composition of mains current and voltage (*b*)

Unlike the welding transformers, the power sources, comprising the electron control circuits, generate much more harmonics of current, it particularly concerns the welding inverters. In spite of advantages (small mass, guarantee of preset shape of external characteristic, high value of cos φ, etc.) the welding inverters generate the widest spectrum of harmonic components of current into mains and distort greatly the sinusoidal curve of current and voltage, therefore, in this case the obligatory application of filters of higher harmonics of current is required. The similar conclusions were made also by the Chinese researchers [14].

The single-phase welding power sources for mains, unlike the three-phase ones, load significantly the neutral wire, not designed for high loads, with higher harmonics of current of zero sequence. Therefore, except the resonance inductive-capacitive filters of higher harmonics of current [15], it is necessary to apply the autotransformer filters of currents of zero sequence [16, 17], used for three-phase four-wire mains. In addition these filters are balancing the mains. They can be connected in parallel with mains at the entrance into enterprise or building or several filters can be used along the length of the mains. In some cases it is rational to apply devices of compensation of reactive power simultaneously with single-phase welding power sources, in which the decreased value of power factor cos φ was observed. In our case these are power sources STSh-250 and VDU-201.

Recommended filters do not almost generate the reactive power, which affects negatively the operation of mains, into the mains and are characterized by improved safety in operation in «non-quality» mains, thus providing the reduction of coefficient THD_I down to 5–15 % in single-phase mains.

The E.O. Paton Electric Welding Institute has a large experience in development of methods of calculation of mains parameters and devices for suppression of higher harmonics of current required for their filtering.

CONCLUSIONS

1. It is shown that the single-phase welding power sources generate higher harmonics of current into the mains, thus deteriorating the quality of electric power. Generation of the 3rd harmonic and harmonics, multiple by it, present a particular hazard.

2. Total value of coefficient THD_I during operation of power sources is 8.7–121.5 %, and coefficient THD_U is equal to 2.2–6.7 %, that proves a poor electromagnetic comparability of single-phase welding supply sources.

3. It was found that the coefficient, accounting for the increase in incremental losses from eddy currents in equipment and mains (K-factor), was equal to 1.3–7.3, that gives no opportunity to refer adequately all the single-phase power sources to the category of energy-saving ones.

4. Rationality and in some cases the necessity were defined for application of filters of higher harmonics of current and filters of current of zero sequence together with single-phase sources of arc supply, reducing the coefficient THD_I to 5–15 %. The application of devices for compensation of reactive power are required for some power sources.

5. It was established that the single-phase transformer power sources (welding transformers with developed magnetic leakage fluxes) and welding power sources (without electron adjustment of current), manufactured on their base, require the obligatory applying of filters of higher harmonics of current.

6. It is shown that the widest spectrum of higher harmonics of current is generated by single-phase welding inverters, distorting most of all the sinusoidal shape of current and voltage of the mains, therefore the obligatory application of filters of higher harmonics of current is required.

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