INFLUENCE OF WELDING POWER SOURCES ON THREE-PHASE MAINS

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Harmonic composition of three-phase electric mains at operation of welding power sources was studied. It is shown that welding sources generate higher current harmonics into the mains that impairs the quality of power. Application of higher harmonic filters is recommended to reduce the impact of welding power sources on the mains

Keywords: *arc welding, power sources, three-phase mains, power quality, higher harmonics, filters*

On the threshold of 1980–1990s developed countries of the world faced the problem of increasing deterioration of the quality of power in the mains, which consisted in distortion of the sinusoidal shape of voltage and current in the mains that led to increased losses and lower reliability of electrical equipment operation. It was the result of a constant increase of power consumption by equipment with non-linear loads, such as rectifiers, inverters, frequency-controlled electric drives, computers, office and other equipment. Non-linear loads generate higher current harmonics into the mains that increase losses in mains wires, equipment and loads, and also impair the electromagnetic compatibility [1–4], i.e. may lead to failure of electrical and electronic equipment, overheating of rotors and accelerated wear of bearings of electric motors and generators, failure of control systems of electric drives and explosions of electrolytic condensates in them, unreliable operation of microprocessor and computational equipment, false operation of the system of protection for electrical equipment switching off, burning of zero wires, fast ageing of the insulation, corrosion of earthing elements, burning of electric lighting instruments, etc.

Three-phase rectifiers with capacitors and different types of inverters generate powerful odd current harmonics, in particular, 5th and 7th, reaching 70–80 % of the main harmonic amplitude [1]. This brings the value of the coefficient of non-linear distortions (harmonics) of current THD_I (total harmonic current distortion) up to 80–90 % [2–4], and in a number of cases even much higher. In IEEE standards (Institute of Electrical and Electronics Engineers, Inc.) [5] acceptable THD_I levels are believed to be $THD_I \leq 5$ % for $k_{Ik} \leq 20$, and ≤ 8 % for $20 < k_{Ik} \leq 50$, for mains of 0.12 to 69 kV voltage, depending on the transmission capacity of the mains and short-circuiting current (here k_{Ik} is the coefficient of short-circuiting current ratio equal to the ratio of short-circuiting current to rated current). Acceptable values of the coefficient of non-linear voltage distortions THD_U (total harmonic voltage distortion) are regarded to be values of up to 3 % for individual nonlinear loads, and for cumulative mains loads the admissible value is equal to 5 % [5]. Local standards [6] allow the value of $THD_U = 8$ %, at which the mains quality already considerably deteriorates.

This undesirable phenomenon can be eliminated by several methods, for instance, increase of the mains power at the expense of commissioning of new power plants and power units or using higher current harmonic filters. Application of filters appears to be more cost-effective and promising.

IEEE Standard 519–1992 [5] which calls on the power users to take measures to suppress higher current harmonics, is valid in North America since 1992. In the countries of the Euro Union, International Standards EN 61000-2-2, -3-2, -6-3, -6-4 have also been introduced in the last few years, which specify the limit levels of higher current harmonics generation for diverse electrical equipment. Work on approval of similar standards is underway in Ukraine and CIS countries.

Equipment for various technologies of welding and related processes, where the electric arc is applied on a mass scale, is a non-linear load. Welding rectifiers and inverters, thyristor power sources of electric furnaces and electrolyzers and other welding equipment also are powerful generators of higher current harmonics. However, welding fabrication has traditionally paid little attention to these problems, although in fabrication of critical welded structures requirements of operation of just one power source were made, so as to eliminate the mutual interference of the power sources.

This may lead to the conclusion about the urgency of the problem of higher harmonics for welding fabrication, particularly, when the issue of promotion of local welding technologies into the developed countries is considered, that is confirmed by the experience of the Chinese experts [7].

The purpose of this paper is assessment of the influence of welding power sources operating in the standard technological mode on three-phase mains, as well as preparing recommendations on reduction of higher current harmonics, generated by them.

A number of welding power sources were tested for this purpose. This paper gives and analyzes the data on four power sources typical for welding and related processes:

- three-phase welding rectifier VDU-305 with thyristor control, which is batch-produced by industry and is designed for coated stick electrode manual arc welding and for consumable electrode gas-shielded arc welding by rectified current of up to 300 A;
- three-phase thyristor pulsed power source I-169 developed by PWI and designed for consumable electrode gas-shielded pulsed-arc welding;
- all-purpose three-phase transistor inverter power source Trans Puls Synergic TPS 5000, commercially produced by Fronius, Austria, and designed for manual, automatic and mechanized, as well as gas-shielded pulsed-arc welding;
- single-phase installation for electroslag remelting UEShP of metals under a flux layer [8], based on R-951 installation, developed at PWI and designed for remelting of copper, nickel, titanium, tungsten and high-alloyed steel.

Chauvin Arnoux C.A. 8230 analyzer (France) of mains quality (single phase) was used as the main measuring instrument. This is an all-purpose instrument, which allows obtaining not only time dependencies of current and voltage with their characteristic values (maximum and minimum value, total, active and reactive power, etc.), but also the harmonic spectra up to maximum harmonic number $h_{max} = 50$. The analyzer has the function of recording and computer connection for further mathematical processing of the data.

Obtained experimental data are used when writing the specification in case of designing the higher harmonic filters, as filters can be used to suppress higher current harmonics and lower the influence of welding power sources on the mains. In addition to experimental data, calculation data were also used when preparing recommendations on lowering the higher harmonics level. These included the following:

Coefficients of non-linear distortions of current THD_I and voltage THD_U [4] are

$$THD_I = \sqrt{\sum_{h=2}^{h_{max}} I_{h\%}^2}\ ; \quad THD_U = \sqrt{\sum_{h=2}^{h_{max}} U_{h\%}^2},$$

where h is the harmonic number; $I_{h\%}$, $U_{h\%}$ are the current and voltage values in percent of the acting current and voltage value of the 1st fundamental harmonic, taken as 100 %: $I_{h\%} = I_h / I_1$, $U_{h\%} = U_h / U_1$.

Another important parameter which determines by how many times additional losses in the electrical equipment and conductors of the mains will increase compared to the case, if only the 1st fundamental current harmonic flowed in the equipment and mains, is K-factor, given by the following formula:

$$K = \frac{\sum_{h=1}^{h_{max}} (hI_{h\%})^2}{\sum_{h=1}^{h_{max}} I_{h\%}^2}.$$

Additional losses are caused by eddy currents, flowing in the current-carrying parts and conductors of the equipment and mains. The eddy currents proper are due to magnetic leakage fluxes, passing through the current-carrying parts and conductors [9].

Obtained experimental and calculated data are summarized in the Table, which has the following designations: I, U are the acting values of current and voltage; $k_{m,\,I}$, $k_{m,\,U}$ are the coefficients of amplitude of current and voltage, equal to the ratio of amplitude values to acting values $k_{m,\,I} = I_m / I$, $k_{m,\,U} = U_m / U$; S, P, Q are the total, active and reactive power, respectively; k_P is the power factor equal to the ratio of active power to total power ($k_P = P / S$); cos φ is the coefficient of phase shift between current and voltage — cosine of angle φ; tg φ is the tangent of angle φ.

Let us consider operation with 50 Hz three-phase AC mains of VDU-305 welding rectifier with connection of power transformer windings — D/Y. Welding of stainless steel 12Kh18N10T was performed with 3 mm stick electrode OZL-8 at welding current of 90 A.

Dependencies of relative values of line current i_* (in the mains line wire) and line voltage u_* in the mains (between two phases) on time t at operation of welding rectifier are given in Figure 1, *a*. Values i_*

Principal parameters of the mains at operation welding arc power sources

Parameter	VDU-305	I-169	TPS 5000	UEShP
I_{m+}, A	27.9	27.5	47.4	149.9
U_{m+}, V	559.0	532.7	557.8	–
I_{m-}, A	−29.1	−28.1	−32.9	−148.3
U_{m-}, V	−559.3	−532.8	−560.2	–
I, A	17.6	15.9	11.2	78.1
U, V	386.6	374.7	396.5	–
S, V·A	6425.4	6175.8	4417.8	–
P, W	5043.1	3917.4	1824.1	–
Q, V·A	3981.5	4774.3	4023.6	–
k_P	0.785	0.634	0.413	–
cos φ	0.797	0.680	0.741	–
tg φ	0.746	1.074	0.877	–
THD_I	16.966	40.709	142.321	27.385
THD_U	2.672	1.039	1.245	–
K	2.348	5.849	43.455	2.452

and u_* are referred to their largest amplitude values: $i_* = i|I_m|$ and $u_* = u|U_m|$, where $I_m = -29.1$ A, $U_m = -559.3$ V, and are shown in the Table, which gives the largest «+» and smallest «−» amplitude values of voltage and current over the period I_{m+}, I_{m-}, U_{m+}, U_{m-}, obtained in the experiment. As is seen from Figure 1, *a*, the current curve shape differs considerably from the sinusoidal curve. Only small breaks are observed on the voltage curve. These qualitative results are confirmed by quantitative results, i.e. diagram of harmonic components of current $I_{h\%}$ and voltage $U_{h\%}$ (Figure 1, *b*). In Figure 1, *b* the values of harmonic numbers are limited by the 27th to improve the visualization of the diagram. From the diagram it is seen that in the supply mains at operation of welding rectifier the following harmonics are manifested: 3rd current harmonic equal to 3 % of the 1st, 5th — 15.2, 7th and 9th — 1.6, 11th — 3.3, 13th — 1.0, 17th — 1.3 %, while the other odd current harmonics do not exceed 1 %. Odd numbers of voltage harmonics exceeding 1 % of the 1st harmonic, have the following values: 5th — 2.3, 7th — 1.1 %. Also manifested are the direct current component at 1.2 % and even current harmonics: 2nd — 4.2, 6th — 1.5 %. The direct component and even harmonics of voltage are negligible.

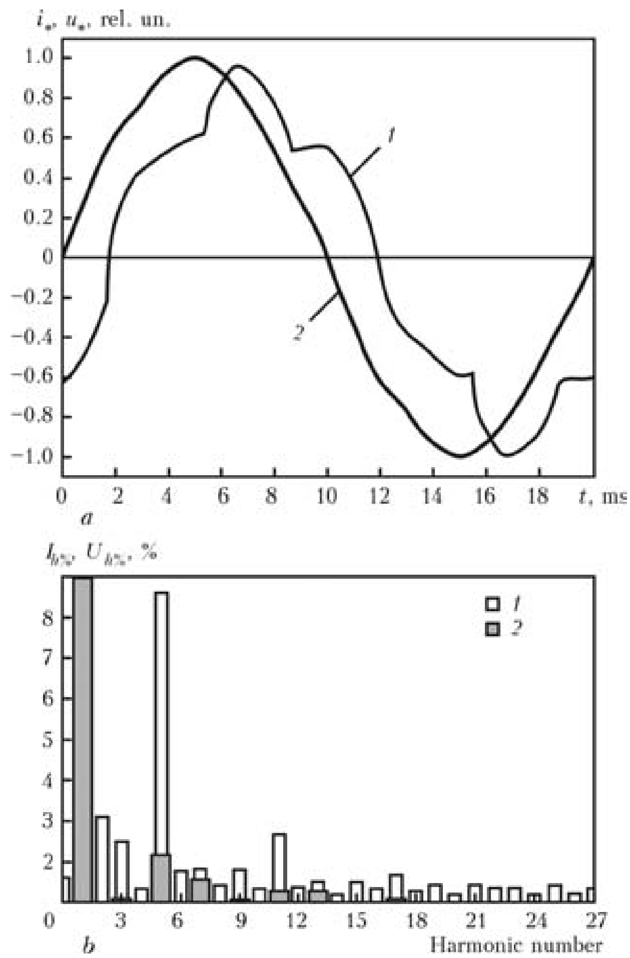

Figure 1. Dependencies of relative values of current (*1*) and voltage (*2*) on time in the mains for three-phase welding rectifier VDU-305 (*a*) and harmonic composition of line current (*1*) and line voltage (*2*) of the mains (*b*)

Coefficients of non-linear distortions of current and voltage are as follows: THD_I = 16.9 %, THD_U 2.7 %, *K*-factor is equal to 2.3. Thus, additional losses in the mains and equipment at operation of the considered welding rectifier at this kind of its loading increase by more than 2 times.

The Table gives the main calculated and experimental values of welding rectifier parameters for VDU-305 at the considered kind of load. These values can change at a change of welding current, but THD_I coefficient can vary in the range of 16–25 %, and THD_U coefficient — in the range of 2.5–3.5 %.

According to the standard [5], acceptable values of THD_I coefficient are in the range of 5–8 %. The studied rectifier exceeds these values by more than 2 times. THD_U value is not exceeded, but the rectifier already can affect the operation of other equipment.

Industrial three-phase welding rectifiers VDU-504-U3 and VDU-506-U have similar characteristics.

Let us consider the influence on three-phase mains of a test sample of three-phase power source I-169 with Y/Y connection of windings of the source power transformer. Welding was performed with 1 mm wire Sv-08G2S in argon and in mixture of Ar + 18 % CO_2, at welding current of 200 A, with pulse repetition rate of 200 Hz and pulse duration of 3 ms.

Time dependencies of relative values of line current and line voltage in the mains at power source operation are given in Figure 2, *a* ($I_m = -28.1$ A, $U_m = -532.8$ V). Although the current curve differs greatly from the sinusoid, the voltage curve is almost undistorted.

From the diagram of harmonic components of acting value of current and voltage (Figure 2, *b*) it is seen that the following current harmonics are manifested in the supply mains at operation of test sample of the power source: 3rd current harmonic, equal to 10.7 % of the 1st harmonic, 5th — 36.3, 7th — 12.4, 11th — 5.7, 13th — 3.4, 17th — 3.1, 19th — 1.45, 23rd — 1.6 % with the other odd harmonics not exceeding 1 %. Voltage harmonics, exceeding 1 % of the 1st harmonic, are only slightly manifested. Even current harmonics are as follows: 2nd — 1.7, 4th — 1.4 %.

Coefficients of non-linear distortions of current and voltage for the 1st harmonics of current and voltage are THD_I = 40.7 %, THD_U = 1.0 %, and *K*-factor is equal to 5.8.

Welding power source has THD_I value exceeding the admissible value [5] by 5 times, THD_U level in this power source is very low, but additional losses in the mains and equipment at power source operation at this kind of its load increase by almost 6 times.

The Table gives the main parameters of power source operation for I-169 at the considered kind of load. At the change of welding mode these values change and THD_I coefficient has rise up to 49 %.

Time dependencies of the relative value of line current and line voltage in three-phase mains at operation of a transistorized inverter power source TPS

5000 are shown in Figure 3, *a*. The greatest amplitude values of currents and voltages are as follows: I_m = = 47.4 A, U_m = −560.2 V.

Figure 3, *b* shows harmonic composition of line current and line voltage at the input of welding power source in welding in mixture of Ar + 18 % CO_2 with 1.2 mm wire at 150 A welding current. Current curve has two clear-cut pulses against the background of almost zero values for the rest of the half-period. The voltage curve, even though similar to a sinusoid, has an almost horizontal turn in the field of the extremums.

Practically all the odd current harmonics are manifested in the source mains, in particular 3rd current harmonic, equal to 42.6 % of the 1st harmonic, 5th — 83.3, 7th — 79.7, 9th — 23.7, 11th — 42.7, 13th — 37.1, 15th — 3.5, 17th — 14.1, 19th — 7.0, 21st — 4.9 %. Voltage harmonics are only slightly manifested. Also manifested in the direct current component at 10.8 % and practically all the even current harmonics: 2nd — 16.9, 4th — 12.1, 6th — 14.3, 8th — 13.1 %.

Coefficients of non-linear distortions of current and voltage for the 1st harmonics of current and voltage are as follows: THD_I = 142.3 %, THD_U = 1.2 %, *K*-factor being equal to 43.5.

The studied power source exceeds the values specified by the standard [5] for THD_I coefficient by 17.7 times, which is indicated by the current curve shape. Here an extremely wide range of harmonic components of current are generated into the mains. Values of THD_U coefficient in this source are greater than those in the previous power source, but they are quite admissible.

Additional losses in the mains and equipment at power source operation with this kind of load increase by more than 43 times.

The Table gives the main parameters of power source operation for TPS 5000 with the considered kind of load. At a change of welding mode these values will change, THD_I coefficient is in the range of 120.5–168.7 %, and THD_U coefficient is in the range of 1.7–1.8 %.

Other inverter welding power sources feature an extremely high level of higher harmonics [10].

Let us show the influence on the mains of operation of single-phase electroslag remelting installation UEShP [8], based on R-951 installation developed at PWI. The high-power installation containing two single-phase transformers TShP 10000 connected in parallel (current in the secondary circuit of one transformer is 10 kA, secondary voltage changes in the range from 42 up to 76 V, transformer rated power is 700 kV·A, maximum power is 760 kV·A, primary voltage is 380 V), thyristor block of current control and smoothing reactor, is connected to two phases of three-phase mains. Time dependencies of relative instant values of current in one of the parallel conductors of the mains powering the installation, are shown in Figure 4, *a*. The greatest amplitude value of current is I_m = 149.9 A. Harmonic composition of line current at the input to the installation at electroslag remelting of metal is shown in Figure 4, *b*. Voltage on installation terminals was not measured because of the complexity of their access.

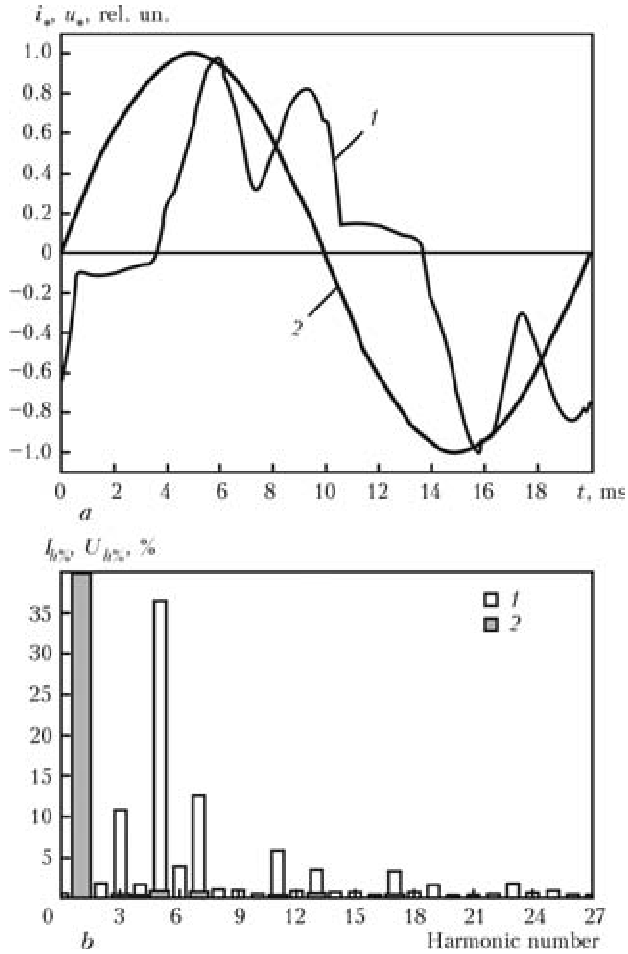

Figure 2. Dependencies of relative values of current (*1*) and voltage (*2*) on time in the mains for a test sample of three-phase thyristor pulse power source I-169 (*a*) and harmonic components of line current (*1*) and line voltage (*2*) in the mains (*b*)

In the mains 3rd current harmonic equal to 24.5 % of the 1st harmonic, as well as 5th — 6.7, 7th — 8.9, 9th — 2.6, 11th — 2.1, 13th — 1.6, 15th — 2.6, 17th — 1.3, 23rd — 1.1 %, are manifested, and the other odd current harmonics do not exceed 1 %. Even numbers of current harmonics are practically absent. Coefficient of non-linear distortions of current for the 1st current harmonic is THD_I = 27.4 %, *K*-factor is equal to 2.4.

Values of THD_I coefficient specified by the standard [5] are exceeded in the installation by more than 3 times. Here, considerable harmonic components of current are generated into the mains. Additional losses in the mains and equipment at installation operation increase by more than 2 times.

The Table gives the main installation operation parameters for UEShP at the considered load type. These values can change at variation of the melting

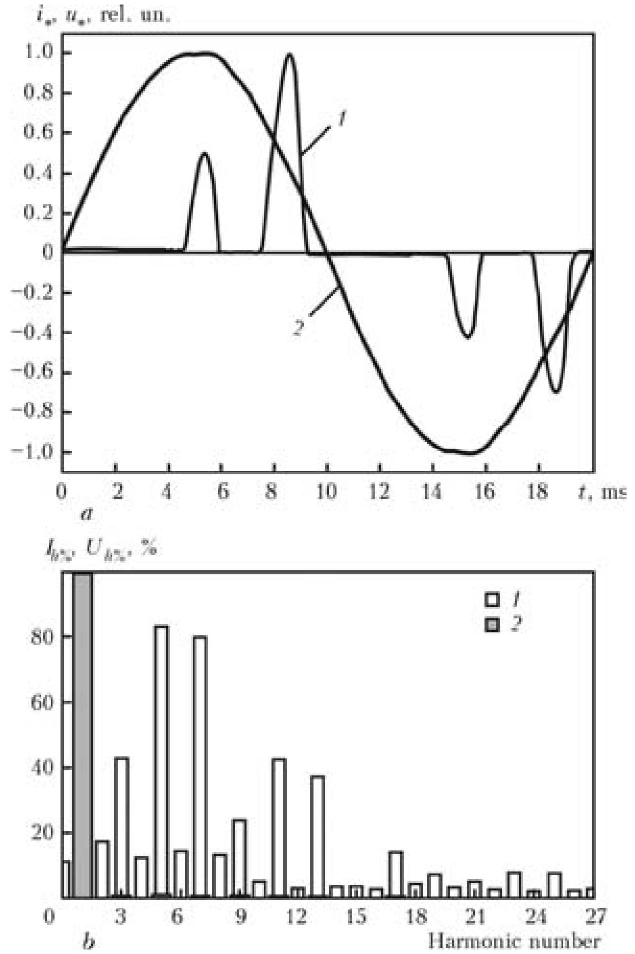

Figure 3. Dependencies of relative values of current (*1*) and voltage (*2*) on time in the mains for versatile three-phase transistor inverter power source TPS 5000 (*a*) and harmonic composition of line current (*1*) and line voltage (*2*) in the mains (*b*)

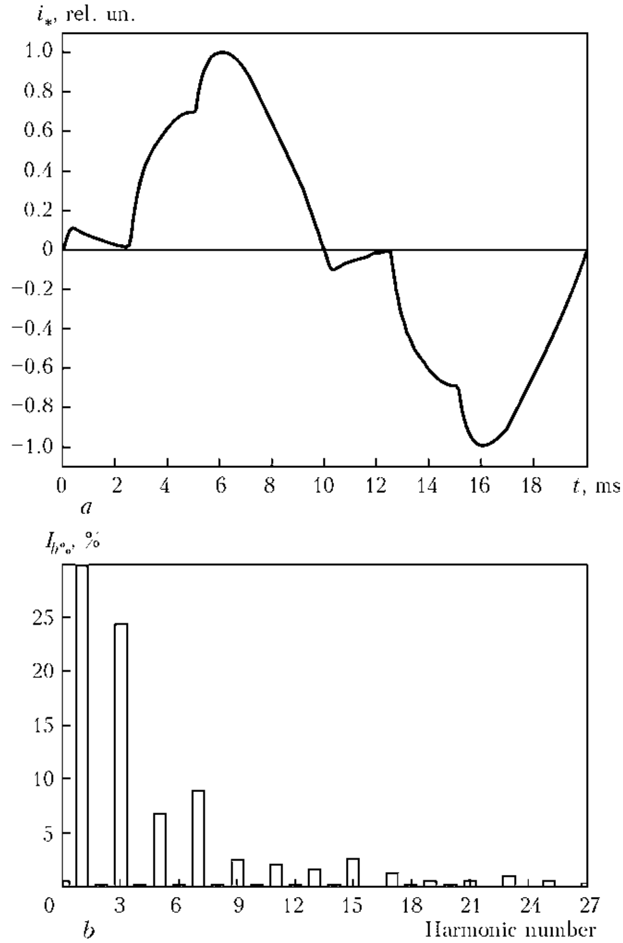

Figure 4. Time dependencies of relative values of current in the mains of UEShP (*a*) and harmonic composition of line current (*b*)

mode, while THD_I coefficient can vary in the range of 25 to 33 %.

As the installation is connected to two phases of the mains, three-phase mains is loaded non-uniformly and its subsequent balancing is recommended.

Thus, in order to improve the power quality and lower the level of higher current and voltage harmonics generated by welding equipment, it is rational, and in a number of cases, necessary to apply filters of higher current harmonics. Here, the welding power sources, in addition to providing the necessary technological parameters, will also have good electromagnetic compatibility, lower the additional losses in the mains wires and equipment connected to the mains.

It should be noted that the positive feature of most of three-phase welding power sources, unlike the single-phase sources, is the fact that they only slightly load the zero wire of the mains by higher current harmonics, that is related to practically uniformly distributed load in the three phases, and in the case of triangle connection of primary windings of the power transformer, current harmonics divisible by three, are decreased.

Lowering of the level of higher current harmonics generated by welding equipment can be performed by the so-called active and passive filters. Active filters containing many elements of both power and microelectronics, are expensive, sophisticated and not always reliable in operation. Therefore, we focused on passive filters, which include:

- three-phase resonance L-C filters of higher current harmonics [11], connected directly at welding equipment input;
- phase-shifting transformer and autotransformer filters of higher current harmonics [1, 4, 12], which also balance the mains. They are connected at the input of a plant or building, having non-linear loads uniformly distributed by phases. Their prototype were devices for three-phase mains balancing [12, 13].

Filters minimize generation of reactive power into the mains, which has an adverse influence on mains operation, and they have a higher reliability at operation in «poor quality» mains, providing lowering of THD_I coefficient to 4–8 %, even in the mains with a high content of higher current harmonics.

The E.O. Paton Electric Welding Institute and Institute of Electrodynamics of the NAS of Ukraine have accumulated extensive experience on development of filters of higher current harmonics in supply mains. Procedures were developed for calculation of mains parameters, required at calculation of the parameters of filters of higher current harmonics and of the procedure of development of the filters proper and their electromagnetic elements.

CONCLUSIONS

1. Value of the coefficient of non-linear current distortions, determining the level of generation of external current harmonics into the mains, at operation of the studied three-phase power sources, is in the range of 16.0–168.7 %, that is much greater than the norms specified by IEEE Standard 519–1992, and is indicative of their poor electromagnetic compatibility.

2. *K*-factor, coefficient allowing for increase of additional losses from eddy currents in equipment and in the mains, was equal to 2.35–43 %, that does not allow including the three-phase welding power sources into the category of power saving.

3. Application of filters of higher current harmonics together with three-phase welding power sources is rational, and in a number of cases necessary, as their application improves the quality of three-phase mains at welding power source operation, lowering the coefficient of non-linear current distortions to acceptable values of 4–8 %.

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