1. Volodymyr TURKOVSKYI[1], 2. Anton MALINOVSKYI[2], 3. Andrii MUZYCHAK[3], 4. Vladyslav LYSIAK[4]

Lviv Polytechnic National University (1,2,3,4)
ORCID: 1.0000-0003-1869-8139; 2.0000-0001-9765-3494; 3.0000-0002-6330-1076; 4.0000-0002-8371-6455

doi:10.15199/48.2023.06.48

The characteristics study of the pilot power supply of a small-capacity electric arc furnace with a non-valve converter "constant current - constant voltage"

***Abstract**. This paper presents the model study results of the modes and indicators of the power supply scheme of a small-capacity electric arc furnace with a non-valve "constant current – constant voltage" converter, aimed at further development, implementation and industrial testing of a pilot charter. The obtained data showed that such converter usage makes it possible to significantly reduce voltage fluctuations, voltage imbalance and the level of higher harmonics in the power system grid. At the same time, there are reduced the amount of reactive power consumption, ensured the smooth adjustment of the arc power, and increased the efficiency of the furnace.*

***Streszczenie.** W tym artykule przedstawiono wyniki modelowych badań reżimów i indykatorów schematu zasilania elektrycznego pieca łukowego małej mocy z bezzaworowym przetwornikiem "stały prąd – stałe napięcie", mających na celu dalszy opracowanie, wdrożenie i przemysłowe testowanie ustawy pilotowej. Uzyskane wyniki wykazały, że zastosowanie takiego przetwornika daje możliwość znacznego ograniczenia wahań napięcia, zmniejszenia asymetrii napięć oraz poziomu wyższych harmonicznych w sieci elektroenergetycznej. Jednocześnie zmniejsza się pobór mocy biernej, zapewniona jest płynna regulacja mocy łuku oraz zwiększa się wydajność pieca. (**Badanie charakterystyk zasilacza pilota elektrycznego pieca łukowego małej mocy z bezzaworową przetwornicą "stały prąd - stałe napięcie"**)*

Keywords: arc furnace, voltage fluctuations, voltage unbalance, power quality, furnace efficiency, power regulation.
Słowa kluczowe: piec łukowy, wahania napięcia, nierównowaga napięcia, jakość energii elektrycznej, wydajność pieca, regulacja mocy.

Introduction

Alternating current electric arc furnaces (EAF) belong to the group of electrical energy consumers whose load is simultaneously dynamic, asymmetric and non-linear. Such load features cause both the power quality decreasing at the coupling point to the electrical grid and the performance worsen of the furnace charter itself. These disadvantages occur due to using a conventional supply circuit (CSC) with operational short-circuit current values in the range of 1.8–3.5 times the nominal arc current.

To improve the electricity quality in EAF supply grids, different dynamic compensation devices are usually used to smooth out the ripples of consumed reactive power. Devices with thyristor-controlled reactor compensator, thyristor-switched capacitor compensator and static compensator (STATCOM) are used the most often. Their usage makes it possible to reduce voltage fluctuations by 1.5-6 times [1], which is not always enough to meet the power systems' requirements [2].

The dynamic compensation devices usage is aimed at reducing the consequences of EAF's negative impact on power grids. At the same time, there is a particular improvement in some operative furnace indicators due to the voltage level increasing at the coupling point of the furnace to the grid. However, the negative impact of dynamic and asymmetric loads on individual indicators of furnace stove practically does not changes or can even slightly increase.

An alternative way of ensuring the EAF electromagnetic compatibility and improving furnaces performance is to reorient the focus of proposed measures from the consequences to the source of negative factor generating. Taking into account the fact that the operational short-circuit for arc furnaces is a normal operating mode, it is proposed to power them through a non-valve converter to form the external power source characteristic in the "constant current" shape with the working section of changing the arc load voltage from zero to the nominal [3]. Considering the peculiarities of reactive power flow, the external characteristic could be supplemented with a "constant voltage" section, i.e. obtain a non-valve converter with characteristic "constant current – constant voltage" (CC–CVC) [4]. The active region of the converter could be the entire range of load changing from operating short-circuit to off mode. At the same time, the calculated values of currents and voltages will not be exceeded in the power supply scheme.

The proposed change in the external characteristic of electric arc furnaces corresponds to the peculiarities of their electrical mode and positively effects the majority of furnace operative indicators.

The research results [4], in which the impact on the EAF power supply grid with 160 MVA transformer powered through a non-valve CC–CV converter was analysed, have shown a reduction in the short-term flicker by 9–16 times. Influence studies of nonlinear asymmetric dynamic modes of such EAF on the furnace indicators have shown [5] that CC-CVC usage increases usable power probable value by 19,5%, reduces power losses by 12,4% and asymmetry factor of grid voltage from 3,66% to 1,35%. Probable currents' levels of higher harmonics have also decreased.

The obtained positive results indicate the expediency of CC-CV converter usage for supplying EAF. At the same time, it is clear that powerful CC-CV charters implementing should be preceded by the completion pilot projects for low-power electric arc furnaces and their industrial testing. The reason is a non-determined dynamic of electromagnetic processes in a furnace caused by stochastic params changes of arc discharge, which are influenced by numerous factors. This is confirmed by the experimental results [6], which show new features of the processes in the arc furnace.

The actual paper presents the research results of CC-CVC modes and indicators for small arc furnace, focused on the further development, implementation and testing of a pilot charter. These results were compared with model data obtained for a CSC of the furnace with the same power.

Research Results

Model studies of the developed CC-CVC scheme under conditions of dynamic, non-linear and asymmetric EAF load were carried out for a furnace with a capacity of 3 tons

(EAF-3). The specified furnace has the following technical characteristics: the furnace transformer power is 2 MWA, the nominal windings voltages are 6 and 0,23 kV, the short-circuit voltage of the transformer unit in the 5th position of the voltage regulator switch is 18,8% and the short circuit losses is 20 kW, the reactive resistance of the short circuit is 1.28 mOhm and the active resistance is 0.86 mOhm.

The structural diagram of EAF-3 power supply with a non-valve CC-CV converter is shown in Fig. 1. It contains inductive (IE) and capacitive (CE) components, the parameters of which are chosen under resonance conditions taking into account furnace transformer (FT) data and provide the formation of an external characteristic section in the modes' range from nominal load to short circuit. Additionally, the specified converter includes non-linear components to form an external characteristic section in the modes' range from nominal load to the off mode. CC-CVC and other consumers are connected to the power supply system (PS) at a point of common coupling (PCC) for which electromagnetic influence indicators are determined.

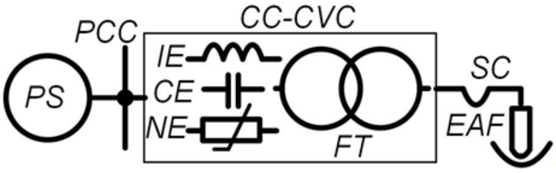

Fig.1. Structural diagram of EAF power supply with a non-valve CC-CV converter

The EAF furnace itself is connected to the secondary winding of the furnace transformer through a high-current system (SC).

Electromagnetic processes in such electrical scheme are described by the following matrix-vector equations system

(1)
$$\mathbf{GMG}_t \frac{d\vec{i}_k}{dt} + \mathbf{GRG}_t \vec{i}_k + \mathbf{G}\left(\vec{u}_n + \vec{u}_c\right) = \mathbf{G}\vec{e}$$
$$\mathbf{C}\frac{d\vec{u}_c}{dt} - \mathbf{G}_t \vec{i}_k = 0$$

where: $\vec{i}_k$ – column vector of contour coordinates of the scheme; $\vec{u}_n$, $\vec{u}_c$, $\vec{e}$ – column vectors, respectively, of non-linear components voltages, of capacitive components voltages, and of motive sources for electrical circuit brunches; **G**, **G**$_t$ – second incidence matrix of the circuit , combined for the branches of electric and magnetic circuits, and its transposed matrix; **M**, **R** – respectively, the matrices of self- and mutual inductances and active resistances of circuit branches, combined for electric and magnetic; $\mathbf{C}$ – matrix of circuit branches' capacities.

To take into account the arc nonlinearity, system (1) is supplemented with an equations system of its model, model, which can be stochastic [7], analytical [8, 9], etc. The Pantegov mathematical model of the arc [8, 9] is used in work. The following system of equations describes this model

(2)
$$\boldsymbol{\theta}_p \frac{d\vec{i}_\theta^{\,2}}{dt} + \vec{i}_\theta^{\,2} = \vec{i}_\alpha^{\,2}$$

where: $\vec{i}_\theta$ – current vector of the static state of the arc column for each of the phases and a given static current-voltage characteristic of the arc; $\vec{i}_a$ – vector-column of phase currents of arcs; $\boldsymbol{\theta}_p$ – diagonal matrix of time constants of the Pantegov arc model.

The model is based on the arc's static current-voltage characteristic, which has a descending character and is given by an equation of the form:

(3)
$$\vec{u}_\theta = u\left(\vec{i}_\theta\right) = U_0 \left(\frac{\vec{i}_\theta}{\vec{I}_0}\right)^n$$

where: U_0, $\vec{I}_0$ – voltages diagonal matrix of the selected points on the static characteristics of arcs in different phases and the corresponding currents vector of these points; n – exponent whose value is negative; $\vec{u}_\theta = u\left(\vec{i}_\theta\right)$ – voltage vector of the arc column static state.

Since the arc column is defined by parameters of both the dynamic and static state, thus equating them, it is possible to obtain the voltage vector of the arc column $\vec{u}_a$:

(4)
$$\vec{u}_\alpha = \vec{R}_{st}\vec{i}_a = \frac{\vec{u}_\theta}{\vec{i}_\theta}\cdot\vec{i}_a,$$

where: $\vec{R}_{st}$ – the resistance of an arc column.

Equations (1)–(4) form a system which solving allows determining the necessary mode params. The research was carried out by simulation in MatLab Simulink.

The conventional scheme of furnace supply shown in Fig. 2 consists of a furnace transformer unit FTU, which includes furnace transformer FT itself and current-limiting (inductive) reactor IR. As in the CC-CVC scheme, the FTU input is connected to the common coupling point PCC of the grid and the output is connected to the arc furnace EAF via a high-current system SC.

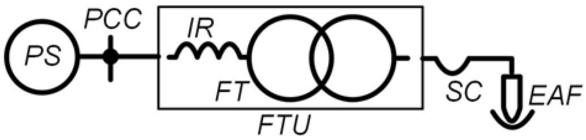

Fig.2. Conventional power supply scheme of EAF

Electromagnetic processes in the conventional scheme CSC are described by equations set (1) excluding the second equation and components $\vec{u}_c$ and $\vec{i}_c$ of the first equation due to the capacitors absence in the scheme. Equations set (2), (3), and (4) that describe the arc nonlinearity remain without changes.

The passport data of the furnace transformer are the same as in the CC-CVC scheme. Calculations for the CSC are performed for the first stage of the regulator switch for which the short-circuit voltage of the transformer unit is 27,6%. The nominal secondary voltages of the furnace transformer in both schemes are equal.

For the proposed options of EAF supply, the scheme of the non-valve CC-CV converter is developed, whose external characteristic, according to the rms currents and voltages, is shown in Fig. 3. The CC-CVC dependency shows that the arc current is almost constant in the operating characteristic range from the operative short circuit to the nominal furnace current. Its instability is near 4% of the nominal current. Thus, the arc current practically does not change under dynamical load conditions; consequently, the losses in furnace transformer windings, high-current system, and electrodes also do not increase. As the arc resistance increases, its voltage increases and reaches a value of 150 V. Further, as the arc resistance increases, its current starts decreasing until the non-working mode occurs.

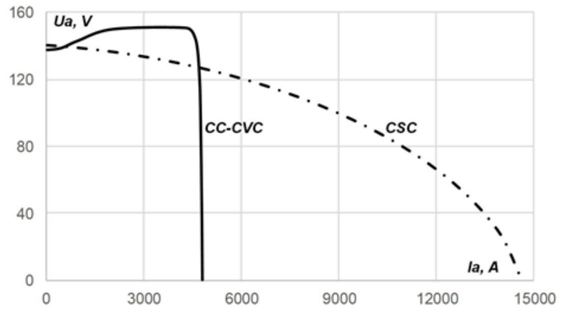

Fig.3. External characteristics of the proposed options of EAF supply

The external characteristic when using the CSC scheme, also given in Fig. 3, shows that operative short circuit increases more than 3 times. Such a sharp increase in current is the main reason for many negative consequences of the impact on the grid and operative indicators of the furnace itself.

Obtained results make it possible to estimate the installed capacities for the main components of the CC-CV converter. Based on the normal operation conditions, the capacitor bank power equals 0.7 of the furnace transformer power, and the electromagnetic reactor power is 0.6. These power values could increase under conditions of abnormal modes; hence, according to the performed assessments, which need experimental approval, such an increase is insignificant.

The main characteristics of the circuit with the CC-CV converter, obtained for quasi-steady modes in the range of load changes from an operative short circuit to an overload based on the active resistance of the arc with a multiplicity of 1.6, are shown in Fig. 4. The results are obtained for a linear symmetric load.

The diagrams of Fig. 4a show the deviation graphs of the root-mean-square currents of the arc I_a, grid I_s, current-limiting reactor I_L, stabilizing capacitor battery I_C, and arc voltage U_a as a function of the change of equivalent resistance arc R_a. All parameters are given in relative units. The nominal arc current of 4750 A and the corresponding current on the higher voltage side using the transformation coefficient K_T=6000/243 are taken as base values. As a base value of the arc voltage is its phase value for the furnace transformer secondary winding – 140.3 V. The changes range of equivalent arc resistance R_a is taken from operative short circuit R_a=0 to multiplicity 1.6 of the nominal value to evaluate the scheme indicators under overload conditions. The base value of furnace transformer power is 2 MW.

As can be seen from Fig. 4a, for changes in the load resistance from an operating short circuit to an overload of 60%, the arc current is practically unchanged I_a=const. Thus, the scheme in question can provide the steady value of the arc current in both the operative range of load changes and under calculated overload. The changes curves in reactor and capacitor bank currents are characterized by a parabolic dependence with minimum values for the load R_a=0,4. Their module sum is a variable parameter, and their vector sum is the arc current I_a, which has an almost constant value.

As seen from the given diagram, the grid current I_s during operative short circuit (R_a=0) is 5 times less than the load current, i.e. in the scheme with CC-CV, such furnace charter mode does not belong to abnormal. The maximal grid current occurs at the maximal load resistance.

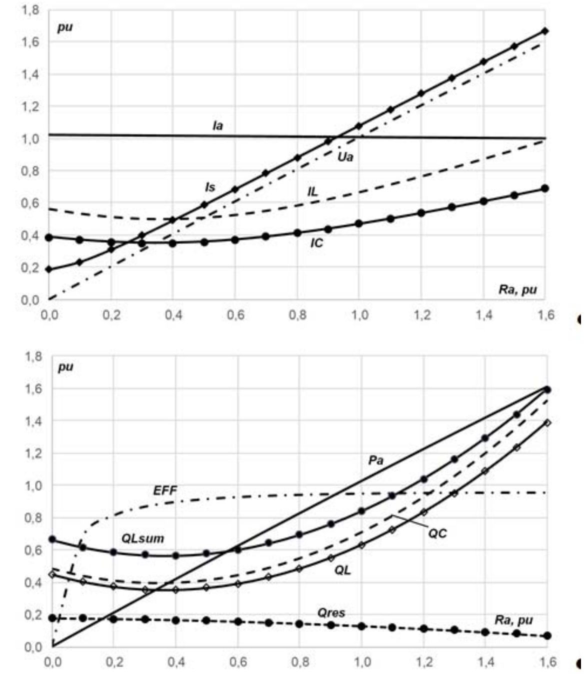

Fig.4. The indicators and parameters dependencies of EAF-3 mode with CC-CV converter on the equivalent arc resistance

Since the arc current is constant, its voltage U_a (Fig. 4a) and active power P_a (Fig. 4b) increase in proportion to the arc resistance. Thus, the proposed scheme allows regulating arc power in a wide range by changing only one parameter – the arc length. This makes it possible to significantly simplify the voltage regulator of the furnace transformer or even refuse its usage altogether.

Fig. 4b shows relative power diagrams of the arc P_a, capacitor battery Q_C, current-limiting reactor Q_L and total power of scheme elements with inductive nature $Q_{L.sum}$, which includes Q_L and reactive power of the high-current system and furnace transformer windings. In the same figure, curves of the change in the energy efficiency factor (EFF) are given.

Diagrams in Fig. 4b show that power of the reactive elements Q_C and Q_L are changing in function of arc resistance according to a parabolic dependence; their powers difference almost does not change. The resulting power Q_{res}, consumed from the grid, has inductive nature and its value in the operative short-circuit mode is less than 20% of the furnace transformer capacity. Additionally, value Q_{res} changes insignificantly under the conditions of arc resistance change. So, in the range of load values from operative short-circuit to the nominal value, the change in the Q_{res} value is 4.8% of the furnace transformer capacity. This indicates that the expected level of voltage fluctuations at the coupling point of the furnace to the grid will be small.

The values of mode parameters and indicators of the conventional furnace supply scheme given in Fig. 5 show that the change in the arc current I_a causes a significant change in reactive power Q. Provided that the load resistance takes on values from zero (operative short circuit) to 1.6 of nominal, the reactive power consumption changes in relative units from 3 to 0.3, i.e. 270%. In the scheme with CC-CVC, such change is only 4.8%.

The dependence $Q(R_a)$ (Fig. 5) shows, that CSC is a significant consumer of reactive power, what requires an appropriate pay or installation of compensation means.

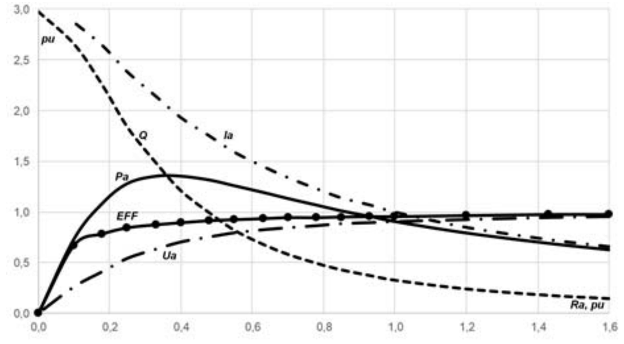

Fig.5. The dependencies of indicators and parameters modes of EAF-3 furnace with CSC on the equivalent arc resistance

The shape of dependency $P_a=f(R_a)$ indicates the impossibility to adjust the arc power by changing only one parameter, i.e. equivalent arc resistance, because while the arc resistance (length) is increasing from zero, the power at first increases over nominal value and then decreases. Simultaneously, the change in the arc length is accompanied by disproportional change in its current.

The functions of an electrical efficiency factor for both schemes are similar and have close values. Note that despite the presence of two additional reactive elements in the CC-CV scheme, the resulting losses practically do not increase. Partially, it is due to the parabolic dependency of reactive elements currents on the arc resistance and to the constant value of the arc current in the scheme with CC-CV. In addition, the main power losses have place in scheme elements for which the proportion of active resistance compare to reactive is significant. This applies to the high-current system of EAF (proportion is 0.14) and the furnace transformer (proportion is 0.1). For the electromagnetic reactor of CC-CV the proportion is 0.016 and for the capacitive battery is 0.005 that is at list one order less.

Voltage fluctuation. The main factor of negative EAF impact on supply grids is voltage fluctuations, because to ensure their permissible values the largest capacity of power system is necessary.

Dynamic modes researches were conducted for different frequencies and amplitude changes load under the conditions of linear problem formulation. At the same time the arc resistance R_a^* changed according to the equation

(5) $$R_a^* = KR_m\left(1 + KR_v \cdot \sin 2\pi f_v t\right)$$

where: KR_m, KR_v – respectively, the average value and amplitude of change in relative arc resistance; f_v – change frequency of the arc resistance.

The nominal equivalent arc resistance is taken as the basic value. During the research, the value of KR_m was assumed equal to one, and KR_v was varied with an amplitude from 0.3 to 0.6. The frequency of load changes is taken from one to 10 Hz.

Researches result showed that the frequency of load changes in the range from 1 to 10 Hz affect voltage fluctuations insignificantly. Thus, at the power of supply system relative to the power of a furnace transformer S_{sc}=100 pu in the supply scheme with CC-CV the load change with KR_v=0,6 and a frequency of 1 Hz causes a voltage change in the grid by 0.028%, and with a frequency of 10 Hz by 0.16%. For the conventional supply circuit, the corresponding voltage changes are also insignificant and equal respectively 1.35% and 1.22% for the same frequencies. As can be seen, in both cases the difference between the limit values of voltage fluctuations in the considered frequency range is only 0.13%.

The influence of supply system power on voltage fluctuations was studied at the frequency of load changes f_v=4 Hz and the change amplitude of a relative arc resistance KR_v=0,6. The obtained results of the voltage change in a grid are shown in Fig. 6.

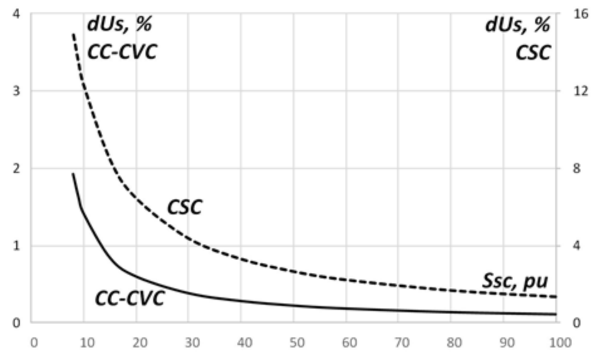

Fig.6. The dependencies of the voltage changes in PCC on supply system power

As can be seen from the diagram (Fig. 6), using a conventional furnace supply scheme in the power system with a relative short-circuit power equal to 100, the dynamic load causes voltage fluctuations in the grid of 1.3%. Reducing the power system capacity to 8 causes the fluctuations increasing up to 15%.

When using a CC-CV converter, voltage fluctuations are reduced to 0.11% and 1.93%, respectively.

Thus, the reduction multiplicity of voltage fluctuations is 12.1 times for high-power supply systems, and 7.8 times for low-power systems. These data refer to charters with a multiplicity of operational short-circuit current of 3.1.

Dynamic load impact. Non-stationary load causes additional power losses in the elements of EAF power supply circuits. The performed calculations for the frequency range of load change from 1 to 10 Hz showed that in CSC for the amplitude change in the relative arc resistance KR_V=0.6, the rms current in a high-current system and a furnace transformer increases by 21% relative to the nominal furnace current.

Under the same conditions, in the scheme with CC-CV, the rms current in a high-current system and furnace transformer windings increases only 0.2–0.6%, i.e. practically does not change. In inductive and capacitive elements of the scheme, the rms current increases by 2.8–3.2% relative to the current at the nominal furnace load.

The power losses in compared schemes were calculated for KR_V=0.6 and f_V=4 Hz. For the CSC scheme, it was found that the total losses in the transformer and high-current system under dynamic load are 124.1 kW. In the scheme with CC-CV the total losses are 110.7 kW, particularly, in the transformer and high-current system 86,9 kW, in the reactor 23.5 kW, and in the capacitive battery 0.3 kW. Calculations were done for the active resistance ratio of the electromagnetic reactor to its reactive resistance of 0.017 and the capacitor battery of 0.0002. Note, that the main losses occur in the high-current system and furnace transformer windings with resistance ratio values of 0.13 and 0.1, respectively.

Arc nonlinearity impact. The study of arc nonlinearity impact on the electricity quality in the grid was carried out using Pantegov analytical arc model, which is described by the equations set (2)–(4). A positive model feature is its high reproduction adequacy of current-voltage arc characteristics, including the shape of its ignition peak.

All calculations were performed for the normal modes set from operative short-circuit current to the nominal load. The values range of supply system short-circuit power was taken from 8 to 100 relative to the furnace transformer power. The supply system grid was reproduced by a series of active-inductive branches with a resistance ratio of 1 to 20.

While calculating the nonlinearity arc influence on the electricity quality in PCC, it was taken into account the completely different nature of arc current change in the compared schemes. Therefore, to ensure the correctness of the result the mode params with arc current values close to the nominal and practically equal values of arc power were analyzed. The obtained results for relative power values of supply system short-circuit Ssc = 100 and 8 are given in Table. 1. In the table, the harmonic components of current and voltage have amplitude values, and other currents and voltages have root-square values. The comparative analysis was performed for symmetric modes according to the 5th harmonic, the value of which is the largest.

Table 1. Indicators of non-linearity arc impact on the electricity quality

Indicators	Dimen-sionality	Scheme options			
		CC-CVC	CSC	CV-CVC	CSC
S_{sc}	pu	100		8	
I_{arc}	A	4902,8	4743,7	4664	4751,9
U_{arc}	V	121,8	125,9	117,6	115,5
P_{arc}	kW	1791,2	1791,3	1646,1	1646,2
I_{sys}	A	182,6	193,1	131,7	193,3
I_{sys5}	A	18,4	22,4	13	17
	%	7,11	8,21	6,96	6,23
U_{sys5}	V	29,8	36,5	144,3	329,3
	%	0,61	0,75	2,95	6,72

From the table data, it can be seen that at S_{sc}=100 the arc powers are almost equal. Arc current values are close enough to the nominal arc current of 4750 A. Under these conditions, the fifth harmonic of the supply system current Isys5 has a value of 18.4 A in the scheme with CC-CV converter and causes the corresponding harmonic appearance of grid voltage which level is 0.61%. For the CSC scheme corresponding level is 0.75%. Resulting, in powerful supply system the arc nonlinearity almost does not have a negative effect on the grid. EAF connection to the supply system with lower power S_{sc}=8 leads to a noticeable increase in the voltage values of higher harmonics in the grid. For the scheme with a CC-CV converter, the fifth voltage harmonic has a value of 2.95%, which is less than the maximum permissible level of 6% for the medium voltage grids of electricity supply [9]. From the table could be seen, that using CSC the fifth voltage harmonic has a value of 6,72% and overseed the permissible level.

Load asymmetry impact. Quantitative characteristics of load asymmetry impact on the electricity quality in a grid were determined for the analysed schemes for the such values combinations of relative resistances linear load in the phases: mode 1 – R_A=R_B=0; mode 2 – R_A=0,5 pu, R_B=0; mode 3 – R_A=0,5 pu, R_B=1 pu. The resistance in phase C in all modes varied from zero to 1.6 of the nominal value. The obtained unbalance values of the negative-sequence voltage component in the grid U_{2S} to the positive-sequence voltage U_{1S} for the relative short-circuit power of the supply system, equal to 8, are given in Table. 2.

The given results show a positive effect of the CC-CVC usage on most indicators and characteristics of the arc furnace. These results could only be confirmed by conducting tests on a real furnace. The pilot project is proposed to be implemented on a small-capacity furnace with a furnace transformer capacity of 2 MVA, and the test scheme can be implemented in a way that includes existing furnace equipment as a component in the SS-CVC scheme without any changes.

Table 2. Indicators of non-linearity arc impact on the electricity quality

Mode	1	2	3	1	2	3
R_{arc}, pu	CC-CVC			CSC		
0	0,00	2,16	3,68	0,21	9,70	8,54
0,25	1,08	1,87	2,81	5,79	7,35	5,39
0,5	2,16	2,15	2,13	9,55	6,98	3,38
0,75	3,23	2,84	1,84	11,74	7,70	2,46
0,9	3,87	3,34	1,93	12,59	8,20	2,37
1	4,28	3,70	2,10	13,03	8,52	2,44
1,1	4,68	4,06	2,34	13,38	8,81	2,57
1,2	5,05	4,42	2,60	13,69	9,08	2,72
1,4	5,68	5,03	3,12	14,15	9,55	3,08
1,6	6,20	5,50	3,32	14,49	9,94	3,43
Middle	3,62	3,51	2,59	10,86	8,58	3,64

The objective of the pilot project research is to assess the efficiency of the circuit in normal and abnormal modes and the features of arc power regulation. During the tests, it is necessary to determine the impact of EAF on power quality indicators, in particular, the levels of fluctuations, unbalance [10, 11] and voltage distortions in different melting periods. The question of the furnace efficiency is also important, in particular, the specific consumption of electricity, electricity losses in the electrical circuits of the furnace charter and the value of electrical efficiency, as well as energy flows and material balance [12]. The amount of reactive energy consumption and the specific consumption of electrodes are also important. It is advisable to determine these indicators for periods of work with different loads. It is also appropriate to evaluate noise levels during furnace operation [13]. Due to the energy amount released in an arc of a unit length for the compared schemes differs significantly, it is advisable to analyze the final metal and the consumption amount of material components [14].

The basis for comparison should be similar indicators of the same furnace with a conventional power supply scheme.

Conclusion

A model of a non-valve converter with external characteristics "constant current - constant voltage" was developed, the parameters of which are adapted to the equipment of the EAF-3 arc furnace, which creates prerequisites for conducting industrial research.

The presented model studies results of such a charter showed that the positive result from its usage is significant even for small-capacity furnaces, since in comparison with the traditional power scheme it allows: to reduce changes in reactive power consumption from 270% to 4.8%; reduce voltage fluctuations in the grid by 12.1 times for the connection of EAF to high-power grids and by 7.8 times for low-power grids; reduce the amount of reactive energy consumption from the grid and the corresponding charge; obtain a wide range of smooth adjustment of the arc power without using a voltage regulator on the furnace transformer; increase the efficiency of the furnace despite the usage of additional equipment (reactor and condenser); reduce the level of negative impact on the power system grid of higher harmonics caused by arc nonlinearity; reduce voltage imbalance in the grid caused by load asymmetry; reduce the noise level during the operation of the furnace.

***Authors**: PhD, Associate Professor Volodymyr Turkovskyi, Lviv Polytechnic National University, Department of Electric Power Engineering and Control Systems, Bandery str., 12, Lviv, Ukraine, 79013, E-mail: volodymyr.h.turkovskyi@lpnu.ua; Doctor of Technical Sciences, Professor Anton Malinovskyi, Lviv Polytechnic National University, Department of Electric Power Engineering and Control Systems, Bandery str., 12, Lviv, Ukraine, 79013, E-mail: anton.a.malinovskyi@lpnu.ua; PhD, Associate Professor Andrii*

Muzychak, Lviv Polytechnic National University, Department of Electric Power Engineering and Control Systems, Bandery str., 12 Lviv, Ukraine, 79013, E-mail: andriy.z.muzychak@lpnu.ua; PhD, Associate Professor Vladyslav Lysiak, Lviv Polytechnic National University, Department of Electric Power Engineering and Control Systems, Bandery str., 12 Lviv, Ukraine, 79013, E-mail: vladyslav.h.lysiak@lpnu.ua

REFERENCES

[1] IEEE Std 1453-2015. (2015). IEEE Recommended Practice for the Analysis of Fluctuating Installations on Power Systems. IEEE Power and Energy Society.

[2] Salor, Ö., Gültekin, B., Buhan, S., Boyrazoglu, B., Inan, T., Atalık, T., Açık, A. … Çadırcı, I. (2010). Electrical Power Quality of Iron and Steel Industry in Turkey. IEEE transactions on industry applications. 46(1). DOI: 10.1109/07IAS.2007.67.

[3] Milyakh A.N., Volkov I.V. Sistemy neizmennogo toka na osnove induktivno-yemkostnykh preobrazovateley (in Russian). [Constant current systems based on inductive-capacitive converters]. Kyiv, Naukova dumka, 1974, p. 216.

[4] Turkovskyi V. H., Malinovskyi A. A., Muzychak A. Z., Turkovskyi O. V. Using the constant current – constant voltage converters to effectively reduce voltage fluctuations in the power supply systems for electric arc furnaces. Eastern-European Journal of Enterprise Technologies, 6/8, (108), 2020, p. 54–63. DOI: 10.15587/1729-4061.2020.219439.

[5] Turkovskyi, V., Malinovskyi, A., Muzychak, A., Turkovskyi, O. (2021). Improvement of electromagnetic compatibility and efficiency of power supply circuits of electric arc furnaces in nonlinear asymmetric modes. Eastern-European Journal of Enterprise Technologies, 5 (8 (113)), 6–16. doi: https://doi.org/10.15587/1729-4061.2021.24314.

[6] Barczentewicz S., Duda K., Bień A. Monitoring of Electric Arc Furnace Supply Voltage Frequency using Phasor Analysis. Przegląd Elektrotechniczny, R. 96 NR 5/2020, p. 51-54. doi:10.15199/48.2020.05.10.

[7] Grabowski D., Walczak J., Klimas M. Electric Arc Furnace Power Quality Analysis Based on a Stochastic Arc Model. 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe. Palermo, Italy. DOI: 10.1109/EEEIC.2018.8494547

[8] Sidorets V. N., Pentegov I. V. Determinirovannyy khaos v nelineynykh tsepyakh s elektricheskoy dugoy. Kiyev: Mezhdunarodnaya assotsiatsiya «Svarka». (Deterministic chaos in non-linear circuits with an electric arc. Kyiv: International Association "Welding"). 2013. – 272 c. DOI: 10.13140/RG.2.1.3777.4883.

[9] Gała M., Rak J., Jagiełа K., Sawicki A. Wpływ zjawisk w obwodzie wielko prądowym na pracę układu zasilania pieca lukowego AC. Przegląd Elektrotechniczny, R. 96 NR 3/2020, s. 67-72. doi:10.15199/48.2020.03.17.

[10] DSTU EN 50160:2014. Kharakterystyky napruhy elektropostachannya v elektrychnykh merezhakh zahal'noyi pryznachenosti. (Characteristics of power supply voltage in electrical networks of general purpose). (EN 50160:2010, IDT). P. 32, 2014.

[11] Olczykowski Z. Electric arc furnaces as a cause of current and voltage asymmetry. Energies, 2021, 14, 5058. https://doi.org/10.3390/en14165058.

[12] Diaconu B., Anghelescu L., Cruceru M. Analysis of energy balance for a steel electric arc furnace. WSEAS transactions on environment and development. V. 16, 2020. P. 48-56. DOI: 10.37394/232015.2020.16.6.

[13] Schwietz J., Panic B. Utilisation of noise level emitted by the electric arc furnace (EAF) for optimisation of the feeding process of slag foaming materials. Metalurgija 61 (2022) 3-4, 753-756.

[14] Moskal M., Migas P., Karbowniczek M. Multi-parameter characteristics of electric arc furnace melting. Materials. 2022, 15, 1601. https://doi.org/10.3390/ma15041601.