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IMPROVEMENT OF ELECTROMAGNETIC COMPATIBILITY AND EFFICIENCY OF POWER SUPPLY CIRCUITS OF ELECTRIC ARC FURNACES IN NONLINEAR ASYMMETRIC MODES

Volodymyr Turkovskyi
Corresponding author
PhD, Associate Professor*
E-mail: volodymyr.h.turkovskyi@lpnu.ua
Anton Malinovskyi
Doctor of Technical Sciences, Professor*
Andrii Muzychak
PhD, Associate Professor*
Olexandr Turkovskyi
Lead Engineer*
*Department of Electric Power
Engineering and Control Systems
Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

AC steel arc furnaces are the most powerful units connected to the electrical grid, the operating mode of which is dynamic, asymmetrical and non-linear. That is why these furnaces cause the entire possible range of negative effects on the quality of electricity in the grid, in particular, fluctuations, asymmetry and non-sinusoidal voltage.

Known proposals for improving the electromagnetic compatibility of electric arc furnaces are mainly focused on eliminating the consequences of their negative impact on the power grid.

The proposed approach and the corresponding technical solution are aimed at reducing the level of generation of a negative factor and at the same time reduce fluctuations, asymmetry and non-sinusoidal voltage. This result is obtained due to the fact that the proposed solution takes into account the peculiarities of the range of modes natural for arc furnaces. Optimal for such consumers is the use of a constant current power supply system I=const in the range of modes from operational short circuit to maximum load and the system U=const in the whole other range of modes. The implementation of such a system is carried out on the basis of a resonant converter «constant current – constant voltage».

Studies have found that the use of such a power supply system, in comparison with the traditional circuit, makes it possible to reduce the non-sinusoidal voltage in a low-power grid from 3.2 % to 2.1 % and the unbalance coefficient from 3.66 to 1.35 %. Previously published data on a significant reduction in voltage fluctuations was also confirmed.

The positive effect of such a system on the energy performance of the furnace itself is shown, manifested in an increase in the arc power by 12.5 %, and the electrical efficiency by 5.1 %. This improves the productivity and efficiency of electric arc furnaces

Keywords: arc furnace, arc model, non-sinusoidality, asymmetry, furnace productivity, efficiency

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1. Introduction

AC electric arc furnaces (EAF) are special consumers of electricity that negatively affect the quality of electricity in the grid, thereby creating problems for other electricity receivers. As a rule, metallurgical enterprises solve these problems by installing devices that improve the quality of electricity in the power grid. Their cost is comparable to the cost of the main technological electrical equipment, which leads to a deterioration in the economic performance of enterprises.

At the same time, arc furnaces are the most common charters for producing high-quality steel and, taking into account the trend towards an increase in the volume of electric steel production, the share of their load in the grids will increase. Considering that powerful technological units have high efficiency, one can expect a further increase in the unit capacity of the furnaces, which may exceed the current maximum of 300 MVA. Thus, the development of the electric steel market does not provide for a decrease in the load on the power grid.

Traditionally used measures to reduce the negative impact of electric arc furnaces on the power supply grid are aimed, as a rule, at eliminating the consequences of the negative impact of furnaces by increasing the power of the power system or using means of dynamic compensation of reactive power.

Despite the use of modern means of dynamic compensation, the negative impact of EAF on the grids remains significant, that is, the problem of the quality of electricity in EAF power grids has not generally been solved.

A change in the paradigm, which consists in the direction of measures not to eliminate the consequences of a negative impact, but to reduce the generation of a factor of negative impact, may allow solving this issue at a different level, at which it becomes possible not only to ensure electromagnetic compatibility to a greater extent, but also to increase the useful power of the arcs and furnace efficiency.

The relevance of the topic and the development lies in the fact that the «constant current – constant voltage» converter (CC-CVC) for powering the EAF makes it possible not only to significantly reduce the negative electromagnetic effect on the power grid, but also to simultaneously improve the energy performance of steel smelting.

2. Literature review and problem statement

AC steel arc furnaces (EAF) are characterized by load, are fast-changing, stochastic, non-linear and asymmetric. When using the conventional furnace power supply circuit circuit (CSS), the features of the electric mode of the furnaces are indicated, causing a decrease in the quality of electricity in the power system grids both at the enterprises of the industry [1] and for groups of furnaces or individual installations [2]. The degree of deterioration in the quality of electricity, despite the use of means of dynamic compensation, is so significant that penalties are imposed on the enterprises of the industry. This indicates the relevance of the topic focused on ensuring the electromagnetic compatibility of arc furnaces with the grid.

Arc furnaces are large consumers of reactive power [3], changes in the value of which cause fluctuations in the voltage in the grid. To reduce voltage fluctuations in electrical grids, various types of dynamic compensation for reactive power are traditionally used. Their use, according to experimental data [4], provides a decrease in the short-term dose of flicker from 6.38 % to 3.31 %. The use of a static synchronous compensator (STATCOM) can reduce the short-term flicker index by a factor of 6, provided that the grid impedance and its changes are properly taken into account [5]. The use of a Static Switched Reactor Compensator (SVC), according to [6], also has a positive effect on the operating characteristics of the furnaces. For the effective operation of compensating means, it is necessary already at the design stage to take into account the specific characteristics of the furnace installation and the features of the grid node [7]. In addition, taking into account the dynamics of the process, an important role in the optimal control of devices is played by the quality of the algorithms for determining the coordinates of the furnace mode, which cannot be directly measured [8].

Given in [5], the maximum reduction ratio of the short-term flicker index for dynamic compensation by a factor of 6 is determined by the modern technical capabilities of power electronics. However, this does not ensure the proper quality of electricity for the use of powerful furnaces in low-power grids. In addition, the positive effect of compensating means on the performance of the arc furnace is rather limited and allows achieving, at best, the nameplate data of the furnace.

Since the electric arc is a non-linear element of the circuit, the furnace generates higher harmonics into the grid. For their studies, arc modeling of EAF arcs is most often carried out by approximating sections of the current-voltage characteristics of the arc by linear/nonlinear segments with/without taking into account the thermal inertia of the arc [9]. In addition, models are used based on artificial neural grids [10] and with reproduction of chaotic processes in an arc [11], etc.

Mathematical models based on the energy balance of the arc column are also often used to study the characteristics of electric arc unit. A survey of such models, in particular, by Cassie and Mayr, was carried out in [12]; the mathematical model of a dynamic arc [13], which was called the Pantegov model in [14], is also described there. The steels of the time of this model can be taken from the data of work [15]. The combined Cassie - Mayr model is also used, the error indices of which were analyzed in [16].

To substantiate the reliability of the reproduction of the arc voltage shape by the considered arc models, the results obtained were compared with the experimental data of the arc voltage functions. The time diagrams of the arc voltage were developed [17], obtained from the measurement data on the secondary winding of the transformer, as well as the experimental data of the arc voltage for a furnace with a transformer power of 60 MVA [18].

Electric arc furnaces are characterized in certain periods of melting by a significantly asymmetric load and, according to experimental data [19], the field of expected values of negative sequence currents is within 15–30 %. This indicates a significant level of mode asymmetry.

Furnace power circuits use dynamic compensation tools that can reduce fluctuations and voltage unbalances in the grid. In fact, such compensators are devices whose action is aimed at reducing the consequences of the negative impact of EAF on the grid.

Conceptually promising is the approach in which the area of action of the funds is directed directly to the source of exposure in order to reduce the level of generation of a negative factor. This can be realized using an inductive-capacitive converter, which can stabilize the alternating arc current and reactive power at the same time and sharply reduce the reactive component of voltage losses in the grid. The characteristics of the resonant converter with galvanic coupling of reactive elements are described in detail in [20].

However, given the peculiarities of chipboards with frequent breaks of arcs and abnormal modes close to this, such converters cannot be directly used for electric arc furnaces. It is necessary that the external characteristic of the converter in the area of operating modes was constant in current, and in the area of abnormal modes – constant in voltage.

A converter with such a characteristic «constant current – constant voltage» (CCCV), allows to schematically stabilize reactive power flows [21] and in dynamic modes to significantly reduce the short-term flicker indicator in the grid [22] with simultaneous equalization of the phase load. An estimate of the power of the equipment required for the implementation of the converter is given in [23]. The analysis of asymmetric modes was carried out taking into account the stochastic nature of the furnace load [24].

Studies [22] showed that the use of a CCCV resonant converter for powering arc steel-making furnaces can reduce the rate of short-term flicker by more than 10 times. These results were obtained by the linear symmetric problem setting and it is necessary to confirm them under conditions of nonlinearity and asymmetry of the load. In addition, under the same conditions, it is necessary to determine the influence of the converter on the main indicators of the operation of the furnace itself, in particular, its productivity and efficiency. To obtain reliable results, it is necessary that the arc model most adequately reproduces its real current-voltage characteristics.

3. The aim and objectives of research

The aim of research is to confirm the effectiveness of the application of the CCCV circuit for powering an arc steelmaking furnace with a nonlinear and asymmetric load. To do this, it is necessary to determine the indicators of the effect on the grid (coefficients of negative sequence and current distortion) and the effect on the indicators of the furnace itself (useful arc power and electrical efficiency). In addition, it is expected to confirm the nonlinear load result for reducing voltage fluctuations by a factor of 10–15, obtained by the linear dynamic load [22].

To achieve the aim, the following objectives were set:

– to develop mathematical models of the considered furnace power supply circuits and to justify the choice of the electric arc model;

– to determine the indicators of the quality of electricity in the grid with a non-linear load;

– to calculate the influence of nonlinear asymmetric load on the main energy characteristics of the furnace regulations and the quality of electricity in the grid.

4. Materials and methods of research

The object of research is two power supply circuits for a large-capacity arc furnace EAF-160 – a traditional power supply circuit for CSS and with the use of CCCV, each of which is powered from a low-power grid. The confirmation of the effectiveness of the application of the CCCV circuit for powering an arc steel-making furnace with a nonlinear and asymmetric load is carried out based on the results of comparing these two options for the power supply circuit.

The essence of the main research hypothesis is that with complete identity of the load characteristics in both cases, the data on the quality of electricity in the grid and the performance of the furnace correspond to the properties of the compared circuits.

In the study, it was assumed that the inductance of a short grid during dynamic changes and unbalanced load does not change; also did not take into account the inter-inductive coupling between the phases of the short grid.

The power system grid in nonlinear modes was reproduced by a simplified equivalent circuit with inductive and active resistances; the ratio of inductive resistance to active resistance is taken equal to 20.

In order to obtain the parameters of the regimes of the CCCV and CSS circuits, necessary for the analysis of the indicators of the quality of electricity and the energy characteristics of the furnace, it is necessary to develop mathematical models of the circuits under study. These models are intended to be generated using matrix methods for analyzing electrical and magnetic circuits, and their implementation is carried out in the MatLab Simulink software environment (USA).

To carry out qualitative studies of circuits with an electric arc, it is necessary to operate with an adequate arc model. The choice of such a model is carried out on the basis of a comparative analysis of the results obtained for the Cassie and Pantegov arc models in the CSS circuit and published experimental data.

The process of calculating asymmetric furnace modes is accompanied by a significant increase in the data array. Their analysis and generalization of the results were carried out taking into account the stochastic nature of the load on the basis of the provisions of the theory of probability. In this case, the real boundaries of the range of values of the mathematical expectation and the standard deviation of the variable coordinate were set.

5. Results of the study of the power supply circuits of the arc furnace in nonlinear asymmetric modes

5. 1. Mathematical models of the furnace power supply circuits and the rationale for the choice of the arc model

A schematic circuit of a furnace power supply with a «constant current – constant voltage» converter is shown in Fig. 1. Its main element is a resonant converter, which consists of inductive L and capacitive C elements, the parameters of which are selected from the resonance condition, taking into account the characteristics of the furnace transformer FT. The circuit is connected to the PS grid at the Point of common coupling (PCC). The SC short circuit connects the secondary turns of the furnace transformer to the actual electric arc furnace (EAF).

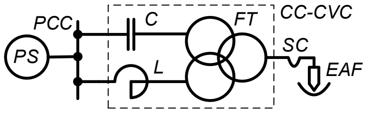

Fig. 1. Schematic circuit of the «constant current – constant voltage» converter

This converter provides a practically constant value of the arc current I_a=const under conditions of load change from the operational short circuit mode to the maximum load (normal mode area). In abnormal modes from maximum load to no-load, the formation of a section of the characteristic is provided, on which the arc voltage is close to the constant U_a=const. The elements for the formation of this section of the characteristic are not reflected in the diagram. Such an external characteristic of the converter provides in normal modes an almost constant value of reactive power consumption and a significant reduction in voltage fluctuations in the grid.

A mathematical model in matrix-vector form has been developed to carry out studies of CCCV and CSS circuits in specified modes (dynamic, nonlinear and asymmetric). The given system of equations (1) describes electromagnetic processes in circuits of various configurations and, to a certain extent, makes it possible to unify the approach to the analysis of mode parameters for various circuits due to the simplified preparation of the input data. System (1) is supplemented with the characteristics of nonlinear elements, in particular, arc models, as well as elements of the formation of the external characteristics of the installation in the area of abnormal modes. This system of equations is as follows:

$$GMG_t \frac{d\vec{i}_k}{dt} + GRG_t\vec{i}_k + G\left(\vec{u}_n + \vec{u}_c\right) = G\vec{e},$$

$$C\frac{d\vec{u}_c}{dt} - G_t\vec{i}_k = 0, \tag{1}$$

where $\vec{i}_k$ – column vector of the outline coordinates of the circuit; $\vec{u}_n$, $\vec{u}_c$, $\vec{e}$ – column vectors, respectively, of voltages of nonlinear elements, voltages of capacitive elements and EMF of branches of an electric circuit; G, G_t – the second incidence matrix of the circuit graph, combined for the branches of electric and magnetic circuits, and its transposed matrix; M, R – matrices of own and mutual inductances and active resistances of the circuit branches, respectively, combined for electric and magnetic circuits; C – matrix of capacities of circuit branches.

To take into account the nonlinearity of the arc, system (1) is supplemented by a system of equations for its model. The work uses the mathematical model of the Pantegov arc [16]. The rationale for the choice of this model and its parameters are given below. This model is described by the following system of equations:

$$\theta_p \frac{d\vec{i}_\theta^{\,2}}{dt} + \vec{i}_\theta^{\,2} = \vec{i}_\alpha^{\,2}, \tag{2}$$

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; θ_p – diagonal matrix of time constants of the Pantegov arc model.

The static current-voltage characteristic of the arc has a descending character and is given by an equation of the form:

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

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

Since the resistance of the arc column is determined by the parameters of the dynamic state, on the one hand, and the corresponding parameters of the static state, on the other hand, by equating them it is possible to obtain the voltage vector of the arc column $\vec{u}_a$:

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

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

Equations (1)–(4) form a system, the solution of which makes it possible to determine the necessary parameters of the regime.

The calculation results are obtained in the formats of the instantaneous coordinates of the mode, the effective values of the parameters, harmonic and symmetric components. In asymmetric modes in the absence of zero sequence currents, symmetrical components are also determined at frequencies of 150 and 450 Hz.

Energy models of arcs of Cassie, Mayr, Cassie-Mayr and Pantegov are often used to study electric arc unit. As shown in [12], Pantegov model is generalizing for the above models, whose equations, as a special case, can be obtained for certain values of the constants. Its positive feature is that it relies on a given static current-voltage characteristic.

At the same time, this model of the arc is used mainly for studying the welding arc, the unit power of which, as a rule, is significantly less than the power of the EAF arcs. Since the power of the installation significantly affects the thermal inertia of the processes, it is necessary to refine some parameters of this model, in particular, the thermal time constant θ_p in equation (2) and the constant n in (3).

The thermal time constant of the Pantegov arc model θ_p can be determined from the time constant of the Cassie arc model θ_c from the relation $2\theta_p=\theta_c$ given in [12]. Thus, based on the data on the time constants of the Cassie arc [16], the steel θ_p have the following values: at the beginning of the melting period – 0.1 ms; the end of the melting period – 0.6 ms; during the periods of oxidation – 2 ms and refining – 5 ms.

To determine the exponent of the static current-voltage characteristic of the arc n, a mathematical model has been developed for the traditional furnace power supply circuit, the power circuit of which consists only of the furnace transformer and the reactor.

To simulate electromagnetic processes, the system of equations (1) with the removed second equation with composite capacitive elements is used.

The results are calculated for the traditional power supply circuit for the EAF-160 arc steel-making furnace. Furnace transformer technical data: power 140 MVA; coil voltage 35/1.3 kV; voltage and active losses of the transformer short circuit experience, respectively, 8 % and 0.8 %. The reactive and active resistance of the short grid are 4.75 and 0.68 mΩ, respectively. Taking into account the inductance of the high-voltage reactor and transformer, the total reactance of the circuit is 6.2 mOhm. The multiplicity of the operational short circuit current is 1.9.

Calculations for the traditional power supply circuit for an arc steelmaking furnace with a Pantegov arc model are performed according to the uniform loading of phases. Fig. 2 shows the timing diagrams of the arc current and voltage using the Pantegov model in the CSS circuit at the beginning of the melting period, when $\theta_p=0.1$ ms. For a visual assessment of the influence of the exponent n of the static volt-ampere characteristic of the arc on the shape of the current and arc voltage, this indicator in the diagram is different for each period of the power frequency of 50 Hz. 7 periods, this indicator received the following 7 values (minus sign omitted): 0.01; 0.02; 0.05; 0.1; 0.14; 0.16; 0.18. The results are given for a low-power power system with the value of the short-circuit power of the power system in relation to the power of the furnace transformer $S^*_{SC} = 8$.

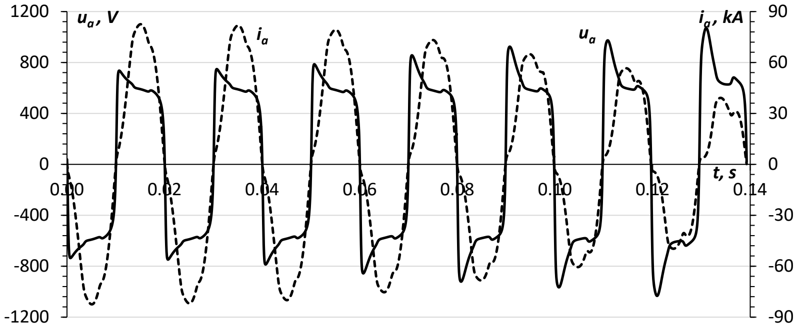

Fig. 2. Timing diagrams of the current and voltage of the Pantegov arc model with different values of *n*

As can be seen from the diagram in Fig. 2, the shape of the arc voltage of the Pantegov model with a time constant of 0.1 ms (the initial melting period) is characterized by the presence of ignition and extinction peaks. With increasing modulus n, the value of the ignition peak voltage increases from 736 V for $|n|=0.01$ and reaches a maximum value of 1070 V for $|n|=0.18$. The extinction peak for the initial value n is barely noticeable. As the modulus of the exponent grows, this peak grows, and with everything in the study, $|n|$ reaches a maximum. The effective value of the arc voltage in the first 2 periods (for the values $|n|$ 0.01 and 0.02) is practically unchanged and amounts to 592 V, and then increases from 594 to 670 V. The effective values of the arc current in the first 2 periods do not decrease significantly, and further sharply decrease from 57 to 42 kA. As can be seen from the diagram in Fig. 5, in the last two periods when $|n|$ gets a value of 0.16 and 0.18, the arc burning mode is close to intermittent. Let's note that the 592 V arc voltage is nominal when the furnace is powered from a low power grid.

The arc current in the first two periods has a nominal value, and further decreases significantly.

For the given curves, the ratio between the voltage of the arc ignition and the voltage of the arc at the moment of its maximum current (relative voltage of the arc ignition) has the following values for the indicated 7 periods: 1.26; 1.27; 1.35; 1.47; 1.59; 1.63 and 1.68. According to the experimental data, during the melting period, this ratio of arc stresses behind the diagrams in [17] is in the range of 1.24–1.76, and for [18] – from 1.46 to 1.6. Thus, in terms of the relative arc ignition voltage, all considered the value of the exponent n make it possible to obtain the shape of the arc voltage, the characteristics of which are consistent with the experimental data.

Thus, the nominal parameters of the furnace mode (under the conditions of the given power of the power system) are provided with values of the modulus n equal to 0.01 and 0.02. Further calculations in the work were performed with the value of this modulus 0.02.

The dynamic volt-ampere characteristics of the arc with the value $\theta_p=0.1$ ms and their static volt-ampere characteristic are shown in Fig. 3.

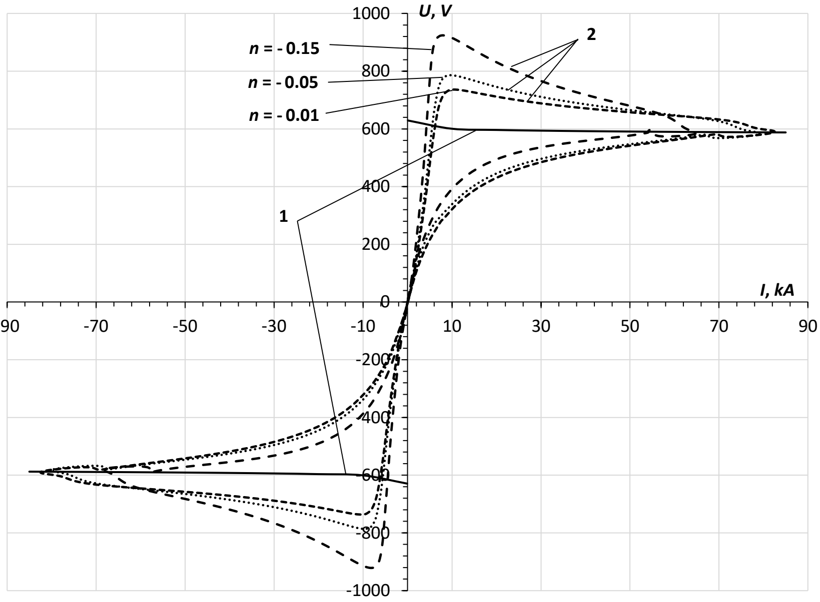

Fig. 3. Static and corresponding dynamic volt-ampere characteristics of the Pantegov arc model: 1 — static characteristic; 2 — dynamic characteristics

A qualitative assessment of the influence of the arc time constant θ_p on the shape of its current and voltage can be made on the basis of the timing diagrams shown in Fig. 4. They are calculated with a variable value of the arc time constant for each period, which acquired the following values: 0.05; 0.1; 0.25; 1.0; 2.5; 4 and 6 ms.

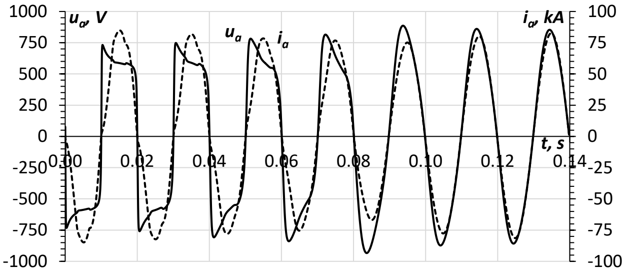

Fig. 4. Timing diagrams of the current and voltage of the Pantegov arc model with different values of the time constant

From the diagrams in Fig. 4 it can be seen that at values of θ_p equal to 6 and 4 ms, the shape of the current and voltage of the arc is almost sinusoidal. Small deviations of these parameters from the sinusoidal form occur at a time constant of 2.5 ms; at $\theta_p<2.5$ ms, current and voltage distortions are significant.

To carry out calculations with the Cassie arc model, the first equation of system (1) is supplemented by the following equations of the Cassie model and arc voltage:

$$\frac{\vec{\theta}_c}{\vec{g}_a}\cdot\frac{d\vec{g}_a}{dt}=\frac{\vec{i}_a^{\,2}}{\vec{g}_a^{\,2}\cdot\vec{U}_c^{\,2}}-1,$$

$$\vec{u}_a=\frac{\vec{i}_a}{\vec{g}_a}, \qquad (5)$$

where $\vec{g}_a$ – conductivity of the arc; $\vec{U}_c$ – voltage of the arc column of the Cassie model; is the time constant of the Cassie model.

Fig. 5 shows the timing diagrams of the arc current and voltage, calculated for the following parameter values: $\vec{U}_a=590$ V; $\theta_c=0.1$ ms.

Shown in Fig. 5 mode parameters are as follows: ignition peak voltage – 686.5 V; voltage at the moment of maximum current – 592 V; arc voltage peak value – 590 V; effective current value – 63.5 kA. From the given data, let's obtain the relative value of the arc ignition voltage equal to 1.16.

For a qualitative assessment of the effect of the arc time constant on the shape of the mode coordinates in Fig. 6 shows the time diagrams of the current and voltage of the arc of the Cassie model with the parameter θ_c variable for each period, acquiring the following values: 0.1; 0.2; 0.5; 1, 2.5; 4 and 6 ms. When comparing the diagrams, one should take into account the relationship between the time constants of the arc models $2\theta_p=\theta_c$.

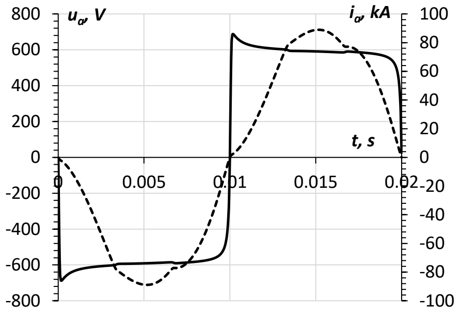

Fig. 5. Timing diagrams of the current and voltage of the arc of the Cassie model

As can be seen from Fig. 6, the time constant significantly affects the shape of the arc voltage. At the same time, the effective value of this voltage is 600 V, it changes only by 0.4 %, that is, it remains practically constant. In this case, the shape of the arc voltage remains non-sinusoidal for $\theta_c=6$ ms.

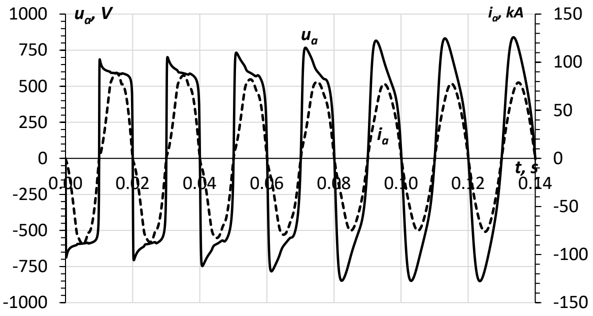

Fig. 6. Timing diagrams of the arc current and voltage of the Cassie model with different values of the arc time constant

The shape of the arc current changes to a lesser extent. The effective value of the current for the first 4 changes of the parameter decreases from 63 kA to 54.3 kA and then remains practically unchanged.

The time diagrams of voltages of the analyzed arc models for the beginning of the melting period ($\theta_p=0.05$ ms, $\theta_c=0.1$ ms) show that the relative arc ignition voltage of the Pantegov model is 1.26, and that of the Cassie model is 1.16. Comparison of these values with experimental data shows that the data of the Pantegov model are included in this range, while the Cassie model is not. This indicates that the Pantegov model adequately reproduces the shape of the arc voltage. In addition, this model has great flexibility due to the variable parameter of the static current-voltage characteristic. In further calculations of the characteristics of the furnace, the Pantegov model was used.

5. 2. Determination of power quality indicators for non-linear load

Calculation results for the CCCV circuit. The defining indicator of the negative impact of EAF on the grid is, as a rule, voltage fluctuations. The calculation of voltage fluctuations at the common point of the power system and the furnace is carried out according to the uniform loading of phases in the range of operating modes. It is assumed that the load changed from an operational short circuit to a value at which the arc voltage is 10 % higher than the rated one. The range of the relative short-circuit power of the power system S^*_{SC} is considered from 8 to 100 units of the nominal power of the furnace transformer (relative units – pu). It is assumed that the parameter of the arc model is $n=-0.02$.

The results obtained for a set of quasi-static modes at the beginning of the melting period, that is, with a value of $\theta_p=0.1$ ms, are shown in Table 1.

Table 1

Dependence of voltage changes in the grid on the power of the power system

S^*_{sc}	*pu*	8	10	30	50	70	100
dU_s	%	0.37	0.37	0.21	0.14	0.10	0.07

The level of higher harmonics in the elements of the EAF power supply circuit is most influenced by the arc burning time constant θ_p. The influence of this parameter on the THD of the arc currents I_a and the grid I_s is shown in Fig. 7 for different values of the time constant in the range from 0.1 to 5 ms. Data are given for nominal arc voltage at power system power ratio of 8.

The maximum THD of the system current is 2.9 % and is approximately half the distortion of the furnace current. This is due to the presence in the CCCV circuit of a branch with an inductive element, the current of which is almost sinusoidal.

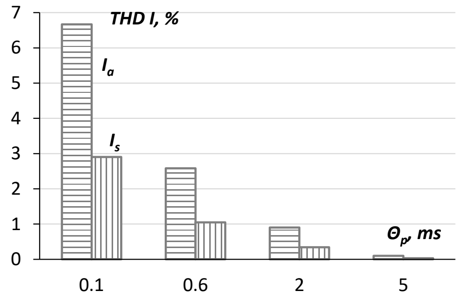

Fig. 7. Dependence of the distortion factor of the furnace and mains currents on the arc time constant

As can be seen from Fig. 7, the maximum value of the non-sinusoidality coefficient of the furnace current is 6.7 % at a constant arc time of 0.1 ms. With an increase in the value of this constant, the THD value rapidly decreases and for $\theta_p=5$ ms, the arc current distortion becomes less than 0.1 %, that is, the arc current is almost sinusoidal.

Harmonic components of the current cause distortion of the voltage. With a time constant $\theta_p=0.1$ ms and the power of the power system $S^*_{SC}=8$, the THD_U of the system at maximum load is 2.1 %. The fifth harmonic is the most significant, with an average value of 1.7 %.

When using the CCCV, there is a certain instability of the arc current. The numerical value of this instability is characterized by the instability coefficient β – the ratio of the difference between the operating short-circuit currents of the furnace and the rated load to the rated load current.

Table 2 shows the values of the instability coefficient of the effective values of the arc current β as a function of the arc time constant θ_p and the relative short-circuit power of the power system S^*_{SC}.

In order to be able to compare with the linear loads of the furnace in the grid $S^*_{sc}=8$, the arc current instability coefficient was calculated, the value of which is 5.7 %.

Table 2

Arc current instability coefficient value, %

θ_p, ms	System short circuit pow S^*_{sc}, pu					
	8	10	30	50	70	100
0.1	0.84	0.79	0.88	0.93	0.96	0.99
0.6	1.60	1.45	1.30	1.32	1.33	1.34
2	3.69	3.28	2.43	2.32	2.27	2.24
5	5.07	4.50	3.28	3.09	3.01	2.96

From given in Table 2 numerical data, it can be seen that the nonlinearity of the arc noticeably affects the degree of current stabilization. In particular, for the smallest of the analyzed power system capacities, the current instability decreases from 5.7 for a linear load to 5.07 for the smallest level of current waveform distortion, which occurs at $\theta_p=5$ ms. An increase in the content of harmonic components with a decrease in θ_p causes an improvement in the stabilizing properties of the circuit and is accompanied by a decrease in β to values less than 1 % for $\theta_p=0.1$ ms.

For large values of the arc time constants equal to 4 and 10 ms, as the power of the power system increases, the instability of the furnace current decreases monotonically.

For values of θ_p equal to 0.6 and 0.1 ms, this dependence is somewhat different, which is explained by an increase in the proportion of harmonic components of the current. At the same time, in the entire range of variation of the power of the power system, the limits of variation of the current instability are rather narrow 0.2–0.3 %.

As can be seen from the data in Table 2, the higher harmonics generated by the arc have, in this case, a positive effect, since they cause an improvement in one of the main characteristics of the CC-CV converter – the degree of stabilization of the arc current.

Calculation results for the CSS circuit. The CSS characteristics for the EAF-160 furnace are calculated under the same conditions, that is, with a symmetrical load for the Pantegov arc time constant $\theta_p=0.1$ ms and the relative power of the grid.

In conditions of low power of the power system in the CSS circuit, there are significant voltage losses in the grid. According to calculations, a change in the mode from an operational short circuit to the rated current of the furnace causes a change in voltage losses from 19.5 to 9.8 %. At the same time, with constant parameters of the circuit equipment under conditions of the rated arc current, its voltage has a value less than the rated voltage, which leads to a decrease in the arc power. Under conditions of load change from the operational short-circuit current to the nominal voltage fluctuation in the grid will be 9.7 %.

Non-linearity of the load causes distortion of the furnace and mains current. For the rated current, the distortion factor of these currents is 4.1 %, and the voltage distortion is 3.2 %. Note that in the CCCV circuit, the voltage distortion coefficient is 2.1 %. These voltage distortion values in both cases are less than the maximum allowable.

5. 3. Influence of nonlinearity and unbalance of the load on the energy characteristics of the furnace and the quality of electricity

The main energy characteristics of furnace power circuits include useful arc power, power losses in circuit elements and electrical efficiency (efficiency, EFF). It is advisable to determine the basic values of these parameters for the rated load for the uniform loading of the phases.

The arc power, taking into account its nonlinearity, can be determined by the effective values of its current and voltage or by the harmonic components of these parameters. In the CCCV circuit, the rated arc power, calculated from the harmonic components, is 105.7 MW. The arc power, calculated for the same conditions according to the active values, is overestimated by 7 %. This is due to the influence of threefold arc voltage harmonics. The results obtained at a constant arc time $\theta_p=0.1$ ms, showed that in modes with a symmetric load THD, the arc voltage is in the range of 41–44 % out of an average value of 42.5 %. Analysis of individual harmonic components of this voltage shows a significant proportion of harmonics that are multiples of three, in particular the third, which is approximately 35 %. In the absence of neutral points of the grid and communication between them, there is no electrical circuit for the passage of zero sequence current. Accordingly, for taking into account only the components accompanied by the occurrence of current harmonics, the averaged distortion factor of the arc voltage will be 24.2 %. Therefore, the calculation of the arc power according to the effective values gives such a significant error.

The calculation of losses in the circuit elements was carried out taking into account the surface effect. According to the ordinal number of the harmonic ν, it is assumed that the growth rate of the resistance of current conductors is $\sqrt{v}$.

Calculations have shown that the increase in electrical losses due to the surface effect for the rated load does not exceed 0.5 %. Such a low level of additional losses is due to relatively small distortions of the current shape.

Power losses in the CCCV circuit take place in the short circuit and the furnace transformer, as well as in the reactive elements of the circuit – the reactor and the capacitor bank and amount to 9.85 MW for the rated load. Calculations have shown that the losses in the short circuit and the furnace transformer are decisive and at maximum load make up 90 % of the total electrical losses statutes.

From the obtained values of power and power losses, the efficiency of the unit (EFF) can be calculated. In terms of uniform loading of phases and rated load, its value is 91.5 %.

The reactive power of the inductive and capacitive circuit elements was determined through the effective values and harmonic components of the mode parameters. For the nominal load mode, the consumption of reactive power from the grid with harmonic components is 45.9 MVAr. The result obtained from the effective values of currents and voltages is less by 6 % due to unaccounted for changes in reactance. The power factor of the installation, determined from the harmonic components of the components, for the rated load is $\cos\varphi=0.93$.

Note that when using the CCCV, an almost constant arc current is maintained, and its voltage is proportional to the equivalent arc resistance. Thus, by changing the arc length, it is possible to obtain a voltage and a high nominal voltage under conditions of low power of the power system.

In the CSS circuit, according to the rated arc current, its active power is 83.5 MW, reactive power – 73.7 MVAr, and power losses – 8.8 MW. According to the efficiency of this mode is 90.5 %, and cos φ=0.78.

The EAF electric arc is a stochastic element of the electric circuit and its parameters vary over a wide range. Despite the use of automatic regulators, the setpoints of which are constant for the individual melting intervals, these changes take place differently in each phase. Therefore, in fact, the entire smelting process occurs with an asymmetric phase load. Under such conditions, an estimate of the averaged parameters of the regime can be obtained only on the basis of probabilistic methods.

The processes occurring in the area of arc burning are characterized by the influence of many random factors and therefore are stochastic and have a certain law of probability density distribution. It is known, according to many studies, currents of arcs of electric furnaces inherent in the normal law of probability density distribution. Accordingly, the resistance of the arc, which leads to a change in the current, and its voltage, will also have a normal distribution. Since the physical processes in the working space of the furnace depend on the furnace supply system, then such a law of the probability density distribution of the variable coordinate takes place not only for the system I=const, but also for the system U=const.

In the system U=const, according to the normal distribution law of the probability density of the arc voltage $f(U_a)$, as a random function unbounded in values, has the following form [24]:

$$f\left(U_a\right)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{\left(U_a-m_U\right)^2}{2\sigma^2}}, \tag{6}$$

where U_a – arc voltage; σ is the standard deviation of the arc voltage; m_U –mathematical expectation of the arc voltage.

In real conditions, the actual value of the arc voltage of the EAF has a limited range of variation from zero to the nominal value U_{2N}. Since the probability of finding the mode in this range should be equal to one, it is necessary to normalize the result by introducing a correction factor h into equation (6).

Taking this into account, the normalized probability density function $f_0(U_a)$ will have the form:

$$f_0\left(U_{arc}\right)=\begin{cases}\dfrac{1}{h\sigma\sqrt{2\pi}}e^{-\frac{\left(U_a-m_U\right)^2}{2\sigma^2}}, & U_a\in\left[0,U_{2N}\right],\\ 0, & U_a\notin\left[0,U_{2N}\right].\end{cases} \tag{7}$$

The value of the correction factor can be determined from the following equation (8) by calculating the values of the Laplace function in the range $0\leq U_a\leq U_{2N}$:

$$h=\frac{1}{\sigma\sqrt{2\pi}}\int\limits_0^{U_{2N}}e^{-\frac{\left(U_a-m_U\right)^2}{2\sigma^2}}\,\mathrm{d}U_a. \tag{8}$$

Thus, using equations (7), the probability of finding the value of the arc voltage in a certain range for a given mathematical expectation and standard deviation of this voltage can be determined. The same probability to have other coordinates of the mode, the quantitative characteristics of which are determined in the same range of arc voltage values. The sum of the interval values of the calculated coordinate, taking into account the correcting factor, will make it possible to obtain the expected value of this coordinate according to the data of one mode. The aggregate of quasi-stationary asymmetric modes can be used to calculate the averaged probabilistic value of the corresponding coordinate. The calculations were carried out for the ranges of values of the mean square deviation from 0.1 to 0.7 and the mathematical expectation of the arc voltage from 0.7 to 1.3 of the nominal.

The results of calculations and processing of asymmetric EAF modes for the power of the power system are given in Table 3 for the traditional power circuit and in Table 4 – for the circuit with CCCV.

Table 3

Probability characteristics of asymmetric CSS modes

Parameters	m_U	Standard deviation, σ						
		0.1	0.2	0.3	0.4	0.5	0.6	0.7
U_{2S}, pu	0,8	3.675	3.676	3.690	3.694	3.697	3.702	3.707
	1	3.628	3.663	3.661	3.662	3.668	3.676	3.685
	1,2	3.891	3.746	3.677	3.656	3.654	3.660	3.668
P_a, MW	0,8	95.1	94.6	93.5	92.4	91.7	91.2	91.0
	1	95.1	93.5	91.9	91.0	90.5	90.3	90.2
	1,2	90.8	89.9	89.3	89.1	89.2	89.3	89.4
dP, MW	0,8	9.67	10.07	10.49	10.77	10.90	10.95	10.94
	1	10.74	11.13	11.39	11.47	11.45	11.39	11.31
	1,2	12.42	12.42	12.30	12.14	11.97	11.81	11.66
EFF	0,8	0.878	0.874	0.869	0.866	0.863	0.862	0.862
	1	0.869	0.864	0.860	0.857	0.856	0.856	0.857
	1,2	0.854	0.850	0.848	0.848	0.850	0.851	0.852
Q_s, MVAr	0,8	58.2	62.3	65.3	66.6	67.1	67.4	67.5
	1	72.9	73.8	73.2	72.1	71.1	70.4	69.8
	1,2	87.9	83.7	79.8	76.9	74.7	73.1	72.0

Table 4

Probability characteristics of asymmetric CCCV modes

Parameters	m_U	Standard deviation, σ						
		0.1	0.2	0.3	0.4	0.5	0.6	0.7
U_{2S}, pu	0.8	1.467	1.470	1.485	1.500	1.512	1.520	1.526
	1	1.181	1.250	1.318	1.374	1.417	1.447	1.469
	1.2	1.166	1.185	1.233	1.292	1.345	1.387	1.419
P_a, MW	0.8	103.4	105.0	106.4	107.0	107.3	107.4	107.5
	1	110.5	110.8	110.3	109.7	109.2	108.9	108.6
	1.2	117.2	115.3	113.5	112.0	111.0	110.2	109.7
dP, MW	0.8	9.69	9.74	9.78	9.80	9.82	9.82	9.83
	1	9.86	9.88	9.88	9.87	9.86	9.86	9.85
	1.2	10.07	10.68	9.97	9.93	9.90	9.89	9.88
EFF	0.8	0.908	0.909	0.909	0.909	0.909	0.909	0.909
	1	0.913	0.912	0.912	0.911	0.911	0.910	0.910
	1.2	0.916	0.915	0.914	0.913	0.912	0.911	0.911
Q_s, MVAr	0.8	47.09	46.46	45.91	45.64	45.51	45.44	45.40
	1	44.34	44.12	44.29	44.53	44.72	44.85	44.95
	1.2	41.41	42.22	42.97	43.57	44.00	44.31	44.53

The following designations are adopted in the Tables 3, 4: P_a – active power of the arc; dP – power losses in circuit elements; Q_S – reactive power of the power system; *EFF* – efficiency factor; U_{2S} – power system negative sequence voltage.

6. Discussion of the results of the study of nonlinear asymmetric modes of the arc furnace power supply circuits

The study of nonlinear modes of the considered circuits was carried out for using the Pantegov arc model. The basis for its choice is the results of comparing the stress diagrams obtained during the studies on the model with experimental data. According to published diagrams of arc voltages [17, 18], the relative value of arc ignition voltage is in the range of 1.24–1.76.

For the Pantegov model, during the research, the relative values of the arc ignition voltage were obtained in the range of 1.26–1.68, and for the Cassie model – 1.16. From these data it can be seen that the ignition voltage of the Pantegov arc model has values falling within the range of 1.24–1.76, but the Cassie model does not. This means that the Pantegov model adequately reproduces the shape of the arc voltage in the initial melting period. Therefore, further calculations were performed using this arc model.

The analysis of arc nonlinearity for voltage fluctuations in the grid was carried out under conditions of changing the furnace mode from an operational short circuit to the rated value of the arc current (voltage). It was found (Table 1) that when using the PSSN circuit, the voltage range is less than 0.4 %. In the circuit with CSS, the change in the load from the operational short-circuit current to the nominal one is accompanied by an unacceptable value of the voltage swing in the grid – 9.7 %. These data confirm the results [22] on the possibility of reducing voltage fluctuations in low-power grids by more than an order of magnitude.

Since an electric arc is an element of an electric circuit with stochastic parameters, the process of steelmaking is always characterized by phase-by-phase asymmetry of the mode parameters. The real set of quasi-stationary asymmetric modes in the field of phase-by-phase variable coordinates (voltage or arc current) is very large. Therefore, obtaining generalized characteristics of such modes is possible only when using the probabilistic approach (equation (6)–(8)). The results obtained for the mathematical expectation of the variable parameter (for the CCCV circuit – the arc voltage, and for the CSS – its current) in the range 0.8–1.2 and the standard deviation from within the values of 0.1–0.7 are given in Tables 3, 4.

Given in Table 3 data shows that under the conditions of changing the CSS mode from the beginning of the melting period ($\sigma=0.7$) to the end of melting ($\sigma=0.1$), the probabilistic average value U^*_{2S} is 3.66 %. This exceeds the value of 2 % allowed by the standard. The data is based on the nominal setting of the automatic current regulator of the furnace $mI^*_a=1$.

When using CCCV, the range of change U^*_{2S} during the entire melting period is in the range from 1.47 to 1.18 % (average – 1.35) at the nominal setting of the furnace voltage regulator $m_U=1$ and meets the requirements of the standard. Thus, for the use of the CCCV, the negative sequence voltage decreased by 2.5 times.

The analysis of the parameters of the mode of the traditional power supply circuit of furnaces in a low-power grid showed that under conditions of constant equipment parameters it is impossible to develop the rated arc power due to large voltage losses in the grid. Therefore, both with symmetrical and unbalanced loads, the arc power is reduced. Under these conditions, an increase in the current setting leads to a further decrease in power, as well as an increase in losses, since the operating point is on the descending section of the $P_a=f(I_a)$ characteristic. As a result, for the period of melting with the setting of the automatic regulator $P_a=f(I_a)=1$, the average expected value of the arc power will be 91.8 MW, and the power loss will be 11.3 MW (Table 4). According to the probabilistic value of the electric efficiency of the furnace, it will have values of 0.85–0.86. Let's note that given in Table 3 the efficiency values were calculated as probabilistic characteristics for a set of their actual values in specific asymmetric modes, and not through the expected values of the arc power and power losses.

The use of the CCCV circuit, as can be seen from the data in Table 4, makes it possible to obtain for $m_U=1$ the probabilistic value of the arc power of 109.7 MW, that is, by 19.5 % more than in the CSS circuit. In the CCCV circuit, a change in the value of mU causes a proportional change in the useful power. Note that the arc power in both cases was calculated from the harmonic components of the currents. In asymmetric modes, the fraction of the arc power due to the symmetrical components of the positive and negative sequence current at frequencies of 150 and 450 Hz was also taken into account. This share for both power supply circuits of the furnace is 0.6–2.8 % of the arc power at the base by harmonics in this mode.

The expected power losses in the equipment are about 10 MW and there is less than in the CSS circuit. According to the CCCV circuit, it provides a high furnace efficiency, the average value of which is 91 % and is almost 6 % higher than when using the CSS circuit.

The obtained positive results indicate that the characteristics of the proposed power supply system correspond to the features of the mode inherent in arc steel-making furnaces. The operating range of such furnaces is the area from the operational short circuit to the maximum operating load. Accordingly, the operational short circuit should be the normal operating mode of the furnace, the current value of which should be close to the nominal one. In the range of modes from maximum operating load to no-load, the circuit should provide a practically constant value of the supply voltage. This is the characteristic of the proposed CCCV circuit.

It is worth noting that the above results were obtained using a study on a mathematical model. Such a model makes it possible to reproduce arbitrary dynamics, nonlinearity, or asymmetry of the regime; however, the mathematical model is not a real arc. Therefore, further research should be carried out with a natural arc.

The development of the research lies in the physical implementation of the circuit. This can be a pilot charter for a low-power furnace or a working model. In the process of implementing such a proposal, questions of equipment parameters may arise, at present it is not serially produced, the purchase of equipment, including for measurements and registration of mode parameters. In addition, the charter must be materialized (physically implemented) at a specific facility. This is possible, but requires appropriate time and other resources.

7. Conclusions

1. The use of the Pantegov arc model in comparison with the Cassie model makes it possible to adequately reflect the current-voltage characteristic of the arc in the initial period of melting. Its positive feature in comparison with other energy models of arcs is based on the static current-voltage characteristic of the arc, provides a better reproduction of the real parameters of the arcs. To reproduce the initial melting period, the constants of this model have the following values: the exponent of the static current-voltage characteristic $n=-0.02$; thermal time constant of the arc $\theta_p=0.1$ ms.

2. Non-linearity of the current-voltage characteristic of the arc causes distortion of current and voltage. In the same characteristics of the arc and the grid, in the case of using the CSS circuit, the distortion factor of the grid current is 4.1 %, and its voltage is 3.2 %. As can be seen from the comparison of the current and voltage distortions, current and voltage distortions for the use of CSS are large, but the voltage distortion value does not exceed the permissible limit of 6 %.

The assessment of additional losses in circuit elements from higher harmonic currents was carried out taking into account the surface effect. An increase in electrical losses at maximum load by 0.5 % was obtained, which indicates a relatively small distortion of the shape of the currents.

Studies have shown that the nonlinearity of the arc significantly affects the degree of stabilization of the effective value of the arc current in the CCCV circuit. It was found that with an increase in the distortion of the arc current, the instability coefficient decreases. It is shown that with a linear load, its value is 5.7 %, and for $\theta_p=0.1$ ms it decreases to 0.84 %, that is, the stabilization of the effective value of the arc current increased by 6.8 times.

3. The results of research in nonlinear asymmetric modes obtained for a low-power grid show that the use of a CCCV converter has significant advantages over the CSS circuit:

– range of voltage change under conditions of changing the mode from the operational short circuit to the rated load decreases from 9.7 to 0.4 %;

– voltage distortion coefficient decreases from 3.2 to 2.1 %;

– the probabilistic value of the voltage unbalance coefficient decreases from 3.66 to 1.35 %;

– probabilistic value of the useful arc power at the nominal setting of the power regulator increases from 91.8 to 109.7 MW (by 19.5 %);

– probabilistic value of the arc power losses at the nominal setting of the power regulator decreases from 11.3 to 9.9 MW (by 12.4 %);

– probabilistic value of the electrical efficiency increases from 86 to 91.1 %;

– probability value of the power factor increases from 0.79 to 0.93.

References

1. Salor, O., Gultekin, B., Buhan, S., Boyrazoglu, B., Inan, T., Atalik, T. et. al. (2010). Electrical Power Quality of Iron and Steel Industry in Turkey. IEEE Transactions on Industry Applications, 46 (1), 60–80. doi: https://doi.org/10.1109/tia.2009.2036547
2. Łukasik, Z., Olczykowski, Z. (2020). Estimating the Impact of Arc Furnaces on the Quality of Power in Supply Systems. Energies, 13 (6), 1462. doi: https://doi.org/10.3390/en13061462
3. Deaconu, S. I., Popa, G. N., Tihomir, L. (2010). Comparative Study for EAF's Reactive Energy Compensation Methods and Power Factor Improvement. WSEAS Transactions on Systems, 9 (9), 979–988. Available at: https://www.researchgate.net/publication/228399802_Comparative_study_for_EAF's_reactive_energy_compensation_methods_and_power_factor_improvement
4. Pérez-Donsión, M., Jar Pereira, S., Soares Oliveira, F. T. (2019). Harmonics and Flicker in an Iron and Steel Industry with AC arc furnaces. Renewable Energy and Power Quality Journal, 17, 417–422. doi: https://doi.org/10.24084/repqj17.329
5. Larsson, T., Poumarede, C. (1999). STATCOM, an efficient means for flicker mitigation. IEEE Power Engineering Society. 1999 Winter Meeting (Cat. No.99CH36233). doi: https://doi.org/10.1109/pesw.1999.747380
6. Parniani, M., Mokhtari, H., Hejri, M. (2002). Effects of dynamic reactive compensation in arc furnace operation characteristics and its economic benefits. IEEE/PES Transmission and Distribution Conference and Exhibition. doi: https://doi.org/10.1109/tdc.2002.1177621
7. Varetsky, Y., Konoval, V., Hanzelka, Z. (2020). A Method of Evaluating FACTS Device Impact on Voltage Flicker in the EAF Supply System. 2020 12th International Conference and Exhibition on Electrical Power Quality and Utilisation- (EPQU). doi: https://doi.org/10.1109/epqu50182.2020.9220317
8. Paranchuk, Ya., Paranchuk, R. (2016). Neural grid system for continuous voltage monitoring in electric arc furnace. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 74–80. Available at: http://nv.nmu.org.ua/index.php/en/component/jdownloads/finish/60-02/8475-2016-02-paranchuk/0
9. Ghiormez, L., Panoiu, M., Panoiu, C. (2013). Harmonics Analysis of the 3-Phase Electric Arc Furnace Using Models of the Electric Arc. AWERProcedia Information Technology & Computer Science, 3, 424–430.
10. Garcia-Segura, R., Vázquez Castillo, J., Martell-Chavez, F., Longoria-Gandara, O., Ortegón Aguilar, J. (2017). Electric Arc Furnace Modeling with Artificial Neural Grids and Arc Length with Variable Voltage Gradient. Energies, 10 (9), 1424. doi: https://doi.org/10.3390/en10091424
11. O'Neill-Carrillo, E., Heydt, G. T., Kostelich, E. J., Venkata, S. S., Sundaram, A. (1999). Nonlinear deterministic modeling of highly varying loads. IEEE Transactions on Power Delivery, 14 (2), 537–542. doi: https://doi.org/10.1109/61.754100
12. Sidorets, V. N., Pentegov, I. V. (2013). Determinirovanniy haos v nelineynyh tsepyah s elektricheskoy dugoy. Kyiv: Mezhdunarodnaya assotsiatsiya «Svarka», 272. doi: https://doi.org/10.13140/RG.2.1.3777.4883

13. Pentegov, I. V. (1976). Matematicheskaya model' stolba dinamicheskoy elektricheskoy dugi. Avtomaticheskaya svarka, 6, 8–12. Available at: https://www.researchgate.net/profile/Igor-Pentegov/publication/320710346_Mathematical_Model_of_a_Column_of_a_Dynamic_Electric_Arc_Matematiceskaa_model_stolba_dinamiceskoj_elektriceskoj_dugi/links/59f6f7700f7e9b553ebd4753/Mathematical-Model-of-a-Column-of-a-Dynamic-Electric-Arc-Matematiceskaa-model-stolba-dinamiceskoj-elektriceskoj-dugi.pdf
14. Savitski, A., Hal'tof, M. (2016). Problemy opredeleniya parametrov matematicheskih modeley elektricheskih dug v tsepyah s istochnikami toka. Elektrichestvo, 1, 25–34.
15. Fomin, A. V. (2009). Construction of imitating model arc the steel-smelting furnace. Izvestiya Tul'skogo gosudarstvennogo universiteta. Tekhnicheskie nauki, 3, 315–321.
16. Golestani, S., Samet, H. (2016). Generalised Cassie–Mayr electric arc furnace models. IET Generation, Transmission & Distribution, 10 (13), 3364–3373. doi: https://doi.org/10.1049/iet-gtd.2016.0405
17. Kolagar, A. D., Pahlavani, M. R. A. (2021). Identification of Plasma Arc Model Parameters in an Electric Arc Furnace Plant via Measurement at the Secondary Side of the Transformer. Journal of The Institution of Engineers (India): Series B, 102 (5), 1079–1089. doi: https://doi.org/10.1007/s40031-021-00622-5
18. Seker, M., Memmedov, A. (2017). An Experimental Approach for Understanding V-I Characteristic of Electric Arc Furnace Load. Elektronika Ir Elektrotechnika, 23 (3). doi: https://doi.org/10.5755/j01.eie.23.3.18328
19. Nikolaev, A. A. (2017). Development of an improved method for selecting the power of a static var compensator for electric arc furnaces. Vestnik of Nosov Magnitogorsk State Technical University, 15 (3), 74–94. doi: https://doi.org/10.18503/1995-2732-2017-15-3-74-94
20. Volkov, I. V. (1974). Sistemy neizmennogo toka na osnove induktivno-emkostnyh preobrazovateley. Kyiv: Naukova dumka, 216.
21. Malinovskyi, A. A., Turkovskyi, V. H., Muzychak, A. Z., Turkovskyi, Y. V. (2019). Peculiarities of the reactive power flow in the arc furnace supply circuit with improved electromagnetic compatibility. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 79–86. doi: https://doi.org/10.29202/nvngu/2019-2/10
22. Turkovskyi, V., Malinovskyi, A., Muzychak, A., Turkovskyi, O. (2020). 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)), 54–63. doi: https://doi.org/10.15587/1729-4061.2020.219439
23. Turkovskiy, V. G., Zhovnir, Yu. M. (2001). Obosnovanie effektivnosti primeneniya ustanovki stabilizatsii rezhima dugovoy staleplavil'noy pechi peremennogo toka. Promyshlennya energetika, 5, 40–44.
24. Kibzun, A. I., Goryainova, E. R., Naumov, A. V., Sirotin, A. N. (2002). Teoriya veroyatnostey i matematicheskaya statistika. Moscow: Fizmatgiz, 202.