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Computer investigation of voltage fluctuations on the power busbars of an arc steel-melting furnace

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ABSTRACT

The intensification of production and the development of electrical technologies result in increased energy intensity and concentration of electrical loads. There is a growing number of nonlinear, phase-asymmetric, and rapidly changing dynamic electricity consumers. Typical representatives of such consumers are arc steel-melting furnaces (ASF). Their operation negatively impacts the quality indicators of electrical energy in distribution networks, necessitating the development of solutions to bring their values within regulatory standards. Traditionally, developed solutions are generally aimed at mitigating the consequences of their operation by increasing the power capacity of the energy system and implementing dynamic reactive power compensation installations. This article proposes a two-loop structure for an automatic control system (ACS) of the electrical regime of ASF. Unlike the aforementioned traditional approach, the solutions proposed in this study are primarily aimed at suppressing disturbances within the power electrical circuits of the ASF itself, significantly reducing the negative impact of their operation on the quality indicators of electrical energy, particularly on voltage fluctuations on the power busbars of the ASF. This is achieved through a substantial increase in responsiveness, phase-wise autonomy in disturbance control, and the expansion of the functional capabilities of the ACS for the electrical regime of the ASF to implement adaptive multi-criteria optimal control strategies. These properties are additionally provided to the control system by the inclusion of a high-speed electrical current control loop in its structure, which functionally enables the formation and rapid implementation of desired artificial external characteristics of the arc furnace. The effectiveness of the proposed solutions was examined using a created computer model of the ACS for the ASF DSP-200, which incorporated the proposed solutions. In the article, a comparative analysis was conducted through computer modeling of the dynamics, electromagnetic compatibility, and energy efficiency indicators of the proposed two-loop ACS and the serial power controller ARDM-T-12 for the ASF DSP-200 arc furnace. The obtained research results confirmed an increase in the dynamic accuracy of stabilizing the coordinates of the electrical regime and a reduction in voltage fluctuations and deviations in the electrical network. Specifically, the current dispersion of the arcs at different technological stages of melting decreased by 4.5-7 times, the electrical network voltage by 3-4 times, and the reactive power by 5-7.5 times.7.5.

Keywords: Arc furnace; computer model; slag fluctuations, dispersion, stabilization, electromagnetic compatibility, artificial external characteristics, energy efficiency

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INTRODUCTION

Arc steel-melting furnaces are among the most powerful consumers of electrical energy. At the same time, they are also among the most potent sources of unstable loads in industrial electrical networks. Arc furnaces operate in a cyclic mode with sharp current consumption, leading to significant voltage fluctuations in the network. They are characterized by a distinctly dynamic, stochastic, nonlinear, phase-asymmetric, and interrelated nature of the load. This negatively affects the quality indicators of electrical energy at the power busbars of arc furnaces. Among the most significant are their impacts on such indicators as voltage fluctuations and deviations, voltage sags, and flicker. It is known

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that for the acceptable connection of several simultaneously operating arc steel-melting furnaces (ASFs) to a general-purpose electrical network, it is necessary to comply with the condition [1]:

$$\sqrt{\sum_{i=1}^{n} S_{AF_i}^2} \Big/ S_{sc} \leq 0.01 \cdot D, \qquad (1)$$

where S_{AF_i} is the nominal power of the i-th furnace transformer with n simultaneously operating ASFs; S_{sc} is the short-circuit power of the electrical network at the point of connection of n arc furnaces; $D = 1$ – for DC ASFs or D=2 – for AC arc furnaces.

Compliance with this condition ensures electromagnetic compatibility. However, in practice, this condition is not always met. When condition (1) is not fulfilled, two schematic solutions are traditionally employed in practice to ensure electromagnetic compatibility:

- appropriate power supply schemes for arc furnaces;
- special filter-compensating devices of direct or indirect action [2].

RESEARCH GOALS AND OBJECTIVES

The goal of the study is to develop solutions aimed at reducing voltage fluctuations in the electrical network at the power busbars of arc furnaces, decreasing their dispersion, and improving other electromagnetic compatibility indicators of arc furnace modes and the electrical network.

The scientific novelty of the research lies in the methodology for the operational formation of desired artificial external characteristics of arc steel-melting furnaces to reduce voltage fluctuations at the power busbars of arc furnaces.

The objective of this research is to use computer modeling methods to investigate and confirm the effectiveness of the developed systems engineering solutions for reducing voltage fluctuations in the electrical network at the power busbars of arc furnaces, as well as improving other electromagnetic compatibility indicators of arc furnace modes and the electrical network.

RELEVANCE OF THE RESEARCH

In the past decade, there has been a continuous increase in global steel production volumes [3, 4]. Concurrently, the volumes of steel produced specifically in arc furnaces have been growing most dynamically. Arc furnaces are widely used in the metallurgical industry for melting high-quality steels and precision alloys, in machine building for die casting, and are among the most unstable loads in electrical networks.

The installed power capacity of the power electrical equipment of these arc steel-melting installations reaches up to 300 MW, and their nominal capacity reaches up to 350 tons [5,6]. Additionally, the specific installed power of their power electrical equipment is increasing, ranging from 0.8-1.2 MW/t in various furnaces.

Currently, these furnaces implement the latest (high) melting technologies "furnace–ladle". According to this technology, the main energy-intensive period of melting the solid charge is carried out in the arc furnace, while the technological stages of oxidation and refining are performed in the ladle. The electrical regime in the ladle is significantly calmer and less energy-intensive. Consequently, the negative impact of their operation on the electrical network is integrally reduced.

The most intense negative impacts on electromagnetic compatibility indicators occur precisely during the main melting stage of the charge in the arc furnace. During the time intervals of this melting stage, the three-phase arc system is characterized by dynamically changing loads and introduces significant nonlinearities and stochastically changing parameters into the power circuit of the arc furnace [5, 6]. As a result of such disturbances, rapidly changing voltage fluctuations occur on the power busbars of the arc furnace, which are assessed by the flicker dose [7]. These devices are also sources of phase asymmetry [8] and distortion of the voltage curve in the electrical network [9].

Flicker is the subjective perception by humans of fluctuations in the luminous flux of artificial lighting sources caused by voltage fluctuations in the electrical network, directly affecting the quality of electrical energy and the operation of other electrical energy consumers connected to the busbars of arc furnaces. The primary cause of flicker is load instability, which causes current and voltage fluctuations in the networks. This phenomenon can manifest through frequent and sharp changes in the level of consumed active and reactive power, causing voltage deviations and fluctuations. In turn, this negatively impacts electronic and lighting equipment, reduces its service life, and increases electrical losses.

In response to this problem, a number of standards have been developed to limit the flicker dose in electrical networks. The most well-known of these is the IEC 61000-3-7 standard, which defines permissible levels of voltage fluctuations for different types of loads. The standard sets limits on short-term and long-term flicker to ensure the stability of electrical networks.

The standard sets limits on short-term and long-term flicker to ensure the stability of electrical networks. The problem of flicker is particularly important because its impact is not limited to individual devices or systems. Flicker can create disturbances in the operation of the entire electrical network, degrading the quality of power supply for consumers. For example, light flickering is one of the most noticeable signs of flicker and can cause discomfort in people. Additionally, certain industrial equipment that depends on voltage stability may also experience operational disruptions [8,9].

ANALYSIS OF RECENT STUDIES AND PUBLICATIONS

The effectiveness of using Active Power Filters (APF) for stabilizing voltage on the power busbars of arc furnaces and stabilizing the reactive power consumption mode of electricity consumers with dynamic loads is presented and evaluated in [10]. A model of the power system with an arc furnace and an active power filter was developed in this study. The results of computer simulations of the power supply modes of a 60-ton arc furnace system showed an improvement in voltage stability.

In [11], based on the finite interval method, a model for predicting voltage fluctuations in the electrical network was developed, and informative parameters influencing the arc combustion process were justified. This model was verified using experimental data, and an information support system was developed for its practical use by electrical network operators to enhance power supply stability.

The analysis of factors influencing flicker during the simultaneous operation of a group of arc furnaces was conducted in [12]. The authors developed a module for its assessment. Using this module, it was shown that the intensity of voltage fluctuations sharply increases when a group of furnaces is operating. A concept was proposed to develop a series of solutions for optimizing the network operation to reduce voltage fluctuations in the case of a group of arc furnaces' operation.

In [13], the authors proposed a method to reduce voltage fluctuations on the power busbars of arc furnaces using an innovative scheme of adaptive notch filters (ANF). The use of Active Power Filters (APF) to reduce flicker caused by the operation of a group of arc furnaces was proposed in [10]. These two schematic solutions are based on compensating harmonic distortions and voltage fluctuations caused by unstable loads of the group of arc furnaces.

In [14] article, various approaches to reducing voltage fluctuations are discussed, particularly the effectiveness of using Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM). These devices operate on the principle of controlling reactive power to stabilize voltage and reduce its fluctuation levels. The authors analyze the effectiveness of these methods under different conditions of distribution networks. The article shows that under conditions of significant load instability, Static Synchronous Compensators demonstrate better results, as they can provide a quick response to changes in the electrical network and stabilize voltage with greater accuracy compared to SVCs, which effectively operate under moderate load instability.

However, the action of the three latest technical solutions is directed towards eliminating the consequences of the negative impact of the operation of a group of arc furnaces on the voltage stability of the electrical network, which, in our view, is less effective than the primary suppression of disturbances in the power circuits of the group of arc furnaces.

The use of fuzzy control principles to improve the dynamics of electrode movement in the process of controlling arc length fluctuations is discussed in [15]. This approach reduces the control time of extreme disturbances and eliminates the oscillation of the transient process when controlling and random fluctuations of arc lengths, thereby increasing the dynamic accuracy of stabilizing other coordinates of the electrical regime.

From the above, it follows that currently one of the most effective ways to combat flicker is the implementation of reactive power compensation systems, harmonic filters, and other technologies to stabilize voltage on the power busbars of arc furnaces. In particular, static reactive power control devices and active power compensators effectively reduce voltage fluctuations and stabilize the operation of the electrical network.

Considering the information from the above publications, it can be stated that the task of developing, researching, and practically implementing special schematic, systems engineering, and algorithmic solutions aimed at comprehensively improving the electromagnetic compatibility indicators of the operational modes of arc furnaces and the electrical network, particularly the suppression of voltage fluctuations in the electrical network, is important and relevant.

PRESENTATION OF MAIN RESULTS OF THE STUDY

The technical solutions analyzed above are aimed at eliminating the consequences of the negative impacts of arc furnace operations on electromagnetic compatibility indicators, particularly on voltage quality and flicker indicators. An alternative and, in our view, more effective approach is the use of solutions focused on the primary suppression of disturbances within the power circuits of the arc furnace group, that is, solutions that eliminate the root cause of voltage fluctuations and flicker.

To implement the aforementioned approach of suppressing voltage fluctuations at the power supply node of the arc furnace, a two-loop structure of the automatic control system (ACS) for controlling the electrical regime coordinates of the arc furnace is proposed, with a functional unit diagram shown in Fig. 1.

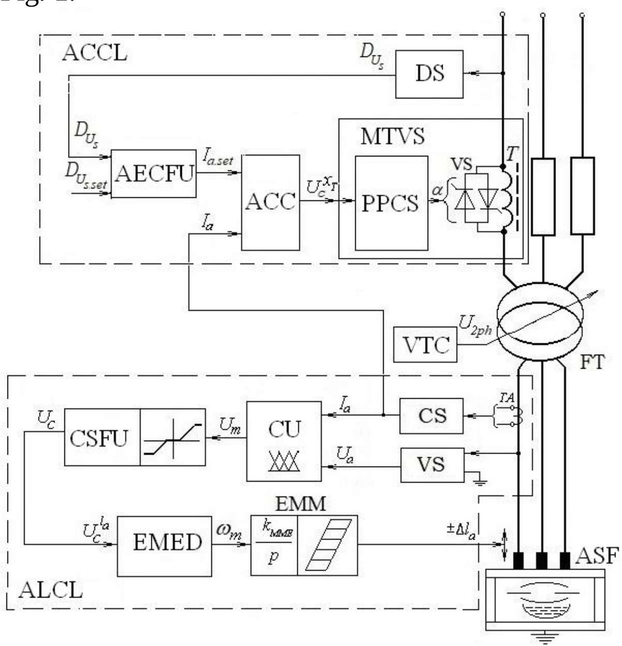


Fig.1. **Functional diagram of a dual-circuit arc furnace coordinate control system**
***Source:* compiled by the authors**

The developed structure implements a model for controlling arc currents and lengths aimed at suppressing voltage fluctuations at the power supply node of the arc furnace and comprehensively improving other electromagnetic compatibility indicators based on enhancing the dynamic control quality of the electrical regime coordinates of the arc furnace.

This structure consists of two loops: a mechanical loop (ALCL) for controlling arc lengths and an electrical loop (ACCL) for controlling arc currents. Disturbance control (deviations of arc lengths and currents from set values) is performed simultaneously, continuously, and independently by both loops.

The mechanical loop in each phase comprises: a current sensor (CS), a voltage sensor (VS) of the arc, a comparison unit (CU) that generates a desynchronization signal between the current and set electrical regime, a control signal formation unit (CSFU) for electrode movement, an electric drive (EMED), and an electrode movement mechanism (EMM). The VTC block switches the voltage stages of furnace transformer FT. The controlling influence of this loop is the controlled $\pm\Delta l_a$ electrode movements in the direction of restoring the arc length to the set value.

The desynchronization signal of the electrical regime $U_{mis}(U_a, I_a)$ in the CU unit is calculated using a fuzzy model that combines the impedance and voltage laws of electrical regime desynchronization [16]. This allows reducing the intensity of phase channel interactions in arc length control and improving the dynamic movement of electrodes during arc length control.

The electrical loop for controlling arc currents (ACCL) operates based on a magneto-thyristor voltage converter (MTVC), an arc current controller (ACC), a dispersion sensor (DS), and a unit for forming the artificial external characteristic of the arc furnace (AECFU). Its controlling influence is the smooth change of the equivalent inductive resistance of the inductors through appropriate thyristor control (T) by the output signal of the pulse-phase control system (PPCS).

A distinctive feature and advantage of the ACCL loop is the high responsiveness of arc current control, enabling the operational, real-time formation of desired artificial external characteristics of the arc furnace (AECFU) and the implementation of desired strategies for adaptive multi-criteria optimal control of the arc furnace and electrical network modes. These properties are additionally provided to the control system by the inclusion of a high-speed electrical current control loop in its structure, which functionally enables the formation and rapid implementation of desired artificial external characteristics of the arc furnace.

To obtain evaluations of the effectiveness indicators of such a two-loop ACS structure for controlling the electrical regime of the ASF and improving electromagnetic compatibility, a computer model was developed in the Simulink application of MATLAB using three-phase instantaneous coordinates. Its basic version is presented in [16, 17], [18, 19], [20, 21], [22].

The created Simulink model was adapted to the parameters of the DSP-200 type arc furnace with an automatic control system based on the typical arc power controller ARDM-T-12 used in this furnace.

The quality indicators of stabilizing the electrical regime coordinates of the arc furnace and the electrical network were studied under stationary random disturbances corresponding to disturbances during the technological stage of solid charge melting when operating the proposed two-loop ACS structure for controlling the electrical regime and, for comparison, when operating only the electromechanical ALCL loop corresponding to the structure of the ARDM-T-12 arc power controller of the DSP-200 arc furnace. For completeness, indicators were also studied at other stages of melting.

In the computer model, to achieve adequate simulation of random disturbances in arc lengths at different technological stages of melting, a "white noise" signal filtered by a low-pass filter was used. The transfer function of the low-pass filter was synthesized to obtain a random signal at its output whose power spectral density function would correspond to the necessary power spectral density function of the random disturbance process in the studied technological melting stage.

For the purity of the experiment, when comparing the indicators of the proposed and known (ARDM-T-12 arc power controller) control system structures at a certain stage, the same realization of the random disturbance process in arc lengths was used, which was simulated in the phase arc intervals over the stationarity interval T=120 s.

When studying the proposed two-loop control system structure, the arc current control loop (ACCL) was tuned to implement the artificial external characteristic 2 (Fig. 2) with an arc current stabilization section at the level $I_{a.st}$ (Fig. 2). The arc current stabilization value was set at the nominal current of the furnace transformer $I_{a.st}$=43970 A Such an artificial characteristic of the arc furnace is one of the feasible ones for reducing voltage fluctuations in the electrical network. In computer studies, the arc current controller was taken as a proportional-integral controller, and its parameters were tuned based on the condition of technical optimum. In general, the stabilization current value $I_{a.st}$ is determined by the technological stage of melting and the required level of dynamic stabilization of arc currents and other electrical regime coordinates.

Fig. 3 and Fig. 4 show only 30-second fragments of the calculated time dependencies of the main electrical regime coordinates changes over the full studied intervals of disturbance stationarity $t \in [0, 120]$c, specifically the processes of controlling phase currents $I_{a_j}(t)$ (j=A,B,C) and electrical network voltages $U_{n_{ij}}(t)$ (ij=AB, BC, CA).

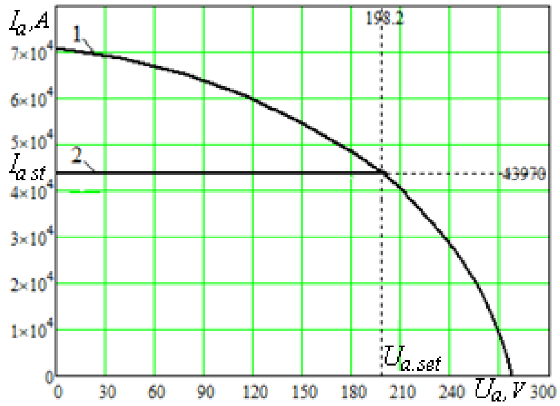
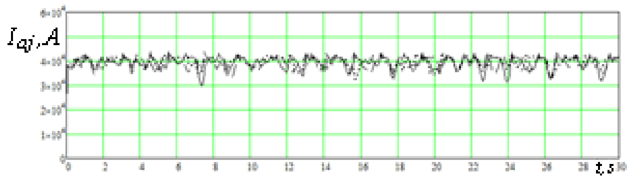
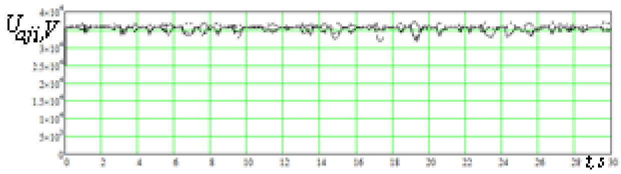


Fig.2. **Natural 1 and artificial 2 external characteristics of the DSP-200 arc furnace with arc current stabilization section at $I_{a.st}$ level**
Source: **compiled by the authors**



a



b

Fig. 3. **Changes of arc current (a) and network voltage (b) on controlling random disturbances using the proposed two-loop ACS electrical regime control structure of the arc furnace**
Source: **compiled by the authors**

In processing the obtained time dependencies of electrical regime coordinate changes in the computer model, the averaged over three phases integral quality indicators (dispersion) and statics (mathematical expectations) of controlling arc currents and voltages, reactive power of the arc furnace, and electrical network voltage at the arc furnace power supply node were determined when operating the proposed two-loop ACS electrical regime control system and when using the typical ARDM-T-12 arc power controller of the DSP-200 arc furnace. These indicators are shown in Table.

Fig. 5 shows the power spectral density characteristic $S_{U_{nAB}}(\omega)$ of the electrical network voltage change process $U_{n_{AB}}$ of the network: 1 – when operating the proposed two-loop AF of the DSP-200 arc furnace; 2 – when operating the ARDM-T-12 arc power controller of this furnace.

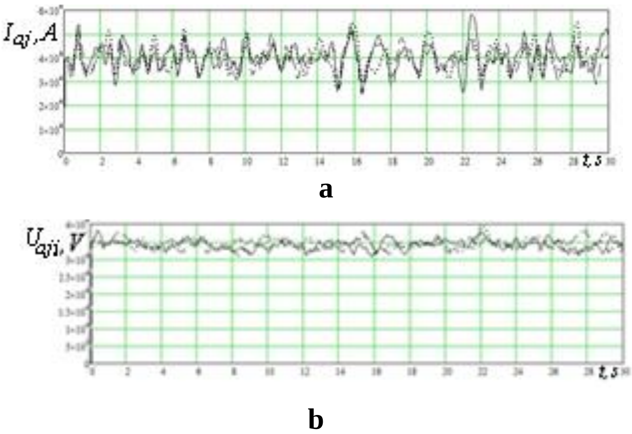


Fig. 4. **Changes of arc current (a) and network voltage (b) on controlling random disturbances using the serial ARDM-T-12 arc power controller**
Source: **compiled by the authors**

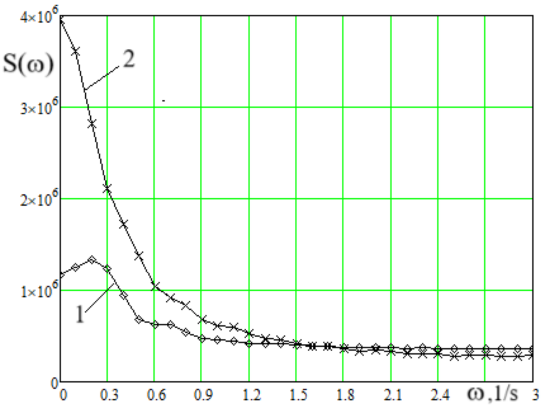


Fig. 5. **Power spectral density characteristic of the electrical network voltage change Process $U_{n_{AB}}$**
Source: **compiled by the authors**

The analysis of the obtained quality indicators of dynamic control of the electrical regime coordinates of the AF under stationary random disturbances during the main solid charge melting stage (Table) illustrates an improvement in the dynamic accuracy of stabilizing the electrical regime coordinates of the AF and a reduction in voltage fluctuations and phase asymmetry [21, 22] at the power busbars of the arc furnace when operating the proposed two-loop ACS electrical regime control system compared to the indicators obtained when operating the ARDM-T-12 arc power controller.

Table. **Mathematical expectations and dispersions of electrical regime coordinates of the studied control system structures of the DSP-200 arc furnace**

ACS structure / Quality Indicators	Two-loop ACS Structure	Controller ARDM-T-12
Arc Voltage, $\overline{U}_a$, V	217.8	218.9
Dispersion, $\overline{D}_{U_a}$, V^2	1189	1121
Arc Current, $\overline{I}_a$, kA	39.2	39.81
Dispersion, $\overline{D}_{I_a}$, kA^2	6.02	34.5
Reactive Power, Q, MVAr	7.47	8.98
Dispersion, $\overline{D}_Q$, MVAr^2	0.79	4.65
Network Voltage, $\overline{U}_n$, kV	34.74	33.96
Dispersion, $\overline{D}_{U_n}$, kV^2	5.33	14.61

Source: **compiled by the authors**

Computer simulations of the dynamics of controlling the electrical regime coordinates of the AF at this and other technological melting stages showed that the dispersion of arc currents decreased by 4.5-7 times, network voltage by 3-4 times, and reactive power by 5-7.5 times. The latter leads to a corresponding improvement in the power factor of the arc furnace.

The obtained computer study results confirm a comprehensive improvement in the energy efficiency and electromagnetic compatibility indicators of the AF and the power supply system, as well as confirm the feasibility of their practical use in AC arc furnaces of various capacities.

CONCLUSIONS

1. As a result of the conducted computer studies, the authors have obtained new knowledge about the impact of the arc furnaces artificial external characteristics with an arc current stabilization section on voltage fluctuations at the arc furnaces power busbars and their impact on other electromagnetic compatibility indicators of the arc furnace and electrical network operating modes.
2. The technical solutions proposed in the article for suppressing voltage fluctuations at the connection node of the arc furnace to the electrical network are simultaneously effective for the comprehensive improvement of the dynamic control indicators of other electrical regime coordinates of the arc furnace and for improving the energy efficiency indicators of the arc furnace and the electrical network
3. The authors' future research will be directed towards creating models of operational adaptive synthesis of artificial external characteristics of the

arc furnace in response to changes in the stochastic characteristics of disturbances based on complex criteria of energy efficiency and electromagnetic compatibility, and developing schematic and structural solutions for their practical implementation in arc furnaces.

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Комп'ютерне дослідження коливань напруги на шинах живлення дугової сталеплавильної печі

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АНОТАЦІЯ

Інтенсифікація виробництва і розвиток електротехнологій обумовлюють зростання енергоємності та концентрації електричних навантажень. Зростає кількість нелінійних несиметричних по фазах та різко змінюваних динамічних споживачів електричної енергії. Типовими представниками таких споживачів є дугові сталеплавильні печі (ДСП). Їх робота спричинює негативний вплив на показники якості електричної енергії у розподільчих мережах, що вимагає розроблення рішень на приведення їх значень до нормативних. Традиційно розроблювані рішення скеровуються, як правило, на усунення наслідків їх дії шляхом збільшення потужності енергосистеми та впровадження установок динамічної компенсації реактивної потужності. У статті запропоновано двоконтурну структуру системи автоматичного керування (САК) електричним режимом ДСП. На відміну від зазначеного вище традиційного підходу, запропоновані у цьому дослідженні структурі рішення спрямовані на першочергове придушення збурень у силових електричних колах самої ДСП, що суттєво зменшить негативний вплив їх роботи на показники якості електричної енергії, зокрема на коливання напруги на шинах живлення ДСП. Отримується це завдяки суттєвому підвищенню швидкодії, по фазної автономізації регулювання збурень та розширенню функціональних можливостей системи керування електричним режимом ДСП на реалізацію стратегій адаптивного багатокритеріального оптимального керування. Ці властивості системі керування надає додатково включений у її структуру швидкодійний електричний контур регулювання струмів дуг та його функціональна можливість формувати та оперативно реалізувати бажані штучні зовнішні характеристики дугової печі. Ефективність запропонованих рішень досліджена на створеній комп'ютерній моделі САК дугової печі ДСП-200 з імплементацією в ній запропонованих рішень. У статті шляхом комп'ютерного моделювання виконано порівняльний аналіз показників динаміки, електромагнітної сумісності та енергоефективності запропонованої двоконтурної системи САК та серійного регулятора потужності АРДМ-Т-12 дугової печі ДСП-200. Отримані результати досліджень підтвердили підвищення динамічної точності стабілізації координат електричного режиму та зниження коливань та відхилення напруги електромережі. Зокрема, дисперсія струмів дуг на різних технологічних стадіях плавки знизилася у 4.5-7 разів, напруги електромережі – у 3-4 рази, а реактивної потужності – у 5-7.5.

Ключові слова: дугова піч; комп'ютерна модель; коливання напруги; дисперсія; стабілізація; електромагнітна сумісність; штучна зовнішня характеристика; енергоефективність

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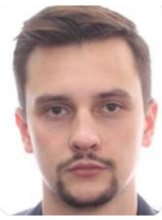

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