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The Study of Dynamics of the Two-Loop Arc Furnace Electric Mode ACS on a Simulink-model

***Abstract**. The structural Simulink-model of the two-loop control system of an arc furnace electric mode is proposed. The structural model of the thyristor-reactor groups is described and the research of the electric mode coordinates control processes was performed. The obtained results confirmed a significant increase of currents regulation speed*

Streszczenie.** Zaproponowano konstrukcyjny model Simulinka układu sterowania z dwiema pętlami w trybie elektrycznym pieca łukowego. Opisano model strukturalny grup tyrystor-reaktor i przeprowadzono badania procesów sterowania koordynacjami w trybie elektrycznym. Uzyskane wyniki potwierdziły istotny wzrost prędkości regulacji prądów. **Badanie dynamiki pieca łukowego przy wykorzystaniu modelu w Simulink.

Keywords: arc furnace, two-loop system, high-speed circuit, computer model, energy efficiency, electromagnetic compatibility.
Słowa kluczowe: piec łukowy, układ dwupętlowy, obwód szybkimodel komputerowy, sprawność energetyczna, kompatybilność EM.

Introduction

The main requirements to the automatic control systems (ACS) of the electrical mode (EM) of electric arc furnaces (EAF) include ensuring high energy efficiency and electromagnetic compatibility. Particularly important this issue is for medium and high capacity arc furnaces (40-250 tons), which are characterized by a large installed capacity of the electrical equipment and its concentrated load on the power supply system. Nowadays, these furnaces are mainly used for melting solid fusion mixture, i.e. they are the sites for implementing major power-intensive melting stages, while the technological stages of oxidation and finishing occur in the ladle. These two factors – a large installed capacity and EM intensification at the stage of solid fusion mixture melting – require a high dynamic accuracy of the EM coordinates' stabilization under the continuous influence of the intensive stochastic and parametric perturbations in the three-phase arcs' power supply circuit. Such adverse mutual effects significantly worsen the quality indicators of electrical power on the EAF power buses and affect the modes and indicators of other electrical power consumers connected to them.

Therefore, the task of devising a high-speed system for regulating electrical mode coordinates, especially the current and arc power, with minimum distortion of the sinusoidality of arc currents in the process of regulating the perturbations of the electrical mode becomes ultimately important.

Unfortunately, EM coordinates' regulation in most modern electric arc furnaces is implemented on the basis of electromechanical and electrohydraulic systems regulating the arc power, the control action of which consists in the relocation of the electrodes aimed at eliminating the perturbations. These systems have a significant mechanical inertia and limited rigidity of the elements of the kinematic scheme of the electrode positioning mechanisms (EPM). Technical capacities of the mentioned systems for raising the operation speed have been practically exhausted. In view of this, a stand-by solution for a comprehensive improvement of the energy efficiency and electromagnetic compatibility indicators of the arc furnace is the improvement of EM control systems aimed at raising the speed of regulation (dynamic accuracy of stabilization) of the arc currents with minimum distortion of their sinusoidality.

In order to increase the speed of regulation of EAF electrical mode coordinates, thereby raising the dynamic accuracy of EM coordinates' stabilization at a set level, and to reduce the voltage fluctuation in the power supply network, Danieli proposed a power supply system for a three-phase electric arc furnace using a saturable reactor [1]. The proposed system has a large installed capacity of the electrical equipment, limited options for implementing the optimal control strategies, whereas the regulation affects the sinusoidality of arc currents.

Research Results

For a significant increase in the regulation speed and a comprehensive improvement of the energy efficiency and electromagnetic compatibility indices, the authors proposed that an additional high-speed electrical circuit for regulating arc currents should be incorporated in the control system. Fig. 1 shows the functional block diagram of the double-loop energy-efficient control system of the electric current (arc power) of the arc furnace [2]. This system consists of a typical electromechanical circuit of regulating the arc length and a high-speed electrical circuit of regulating the arc current. The regulation circuits of the proposed double-loop EM ACS and phase channels of regulation in each circuit operate independently (autonomously) and continually in the process of a control response to coordinate and parametrical perturbations, which occur in the power supply circuit of the three-phase arcs and in the arcs themselves.

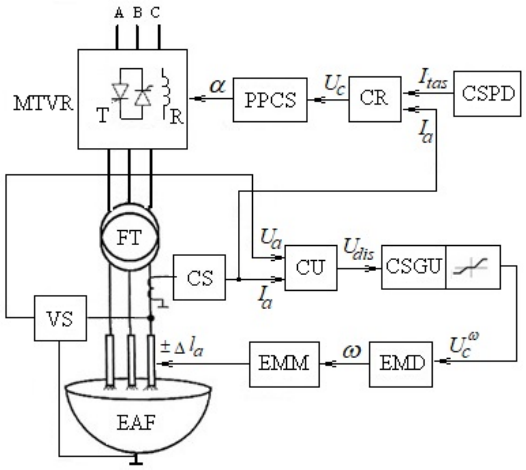

Fig.1. Functional block diagram of the double-loop ACS for EM of the arc furnace

The electromechanical circuit for regulating the electrode position (arc lengths) consist of sensors of effective values of the current (CS) and voltage (VS), a comparator unit (CU) and a control signal generation unit (CSGU), in which the differential law of EM control is implemented, as well as electrode movement drive (EMD) and electrode movement mechanism (EMM). An electrical circuit in each phase is made up of an arc current sensor CS, an arc current set-point device (CSPD), an arc current regulator (CR) and a magneto-thyristor voltage regulator (MTVR).

MTVR are consists of a pulse-phase control system PPCS and reactors R connected in parallel and two thyristors T connected in series in the power supply circuit of the furnace transformer FT.

The developed model takes into consideration all the major non-linearities of the power supply circuit of the three-phase arcs and rigidity parameters of the EMM kinematic scheme elements, adequately simulates parametric and coordinate perturbations in the power supply circuit and dependencies of the dynamic current/voltage diagrams of the arcs, as well as implements a user-friendly interface for changing the ACS structure, laws and parameters, carrying out mathematical experiments and statistical on-line processing of the results.

For the proposed double-loop ACS, it is important to study the dynamics indices of the EM coordinates' regulation and energy efficiency and electromagnetic compatibility indices of the electric arc furnace. In [3], a single-phase Simulink model of the arc power supply system was developed; hence, it has a low accuracy of simulating the arc currents' shape. The authors of [4] have presented a three-phase Simulink model of the arc furnace in the averaged coordinates, which does not allow simulate the changes of the arc voltage and current in the power circuit at the level of instantaneous values.

For this we developed a three-phase Simulink model of the double-loop ACS for the EM of the DSP-200 arc furnace in instantaneous coordinates, the structural block diagram of which is presented in Fig. 2.

The structural elements of the Simulink model simulating the elements of the three-phase arc power supply circuit, the three-phase arcs, the system of automatic regulation of the arc length and generation of random and determined perturbations, and the computing blocks performing on-line statistical processing of the obtained EM coordinates' changes for the melting process are described in [5].

The power elements of the magneto-thyristor voltage regulator are presented in the Simulink model (Fig. 2) by the block MTVR (green), its phase channels of the pulse-phase control system PPCS shows the developed structural Simulink model of one phase of MTVR with three parallel thyristor-reactor groups (PTRG), and Fig. 4 presents the detailed Simulink model of one PTRG.

The PTRG Simulink model shown in Fig. 3 consists of three reactors R connected in series, each of which is connected with a pair of anti-parallel thyristors T. The furnace load currents (i.e., arc currents) are regulated by changing the thyristor control angles, which influences the equivalent inductance of each reactor. The thyristor control angles are formed by PPCS in the function of the output signals of the arc current regulators CR (Fig. 1, Fig. 2).

The integral criterion of the quality of EM coordinates regulation is the arc current dispersion. When dealing with random perturbations, the arc current dispersion is determined mainly by the EM coordinates' ACS operation speed, level of independence of the phase channels of regulation, control law for EM and dependency of the external static characteristic of the arc furnace $I_a(U_a)$. The natural external static characteristic of the arc furnace $I_a(U_a)$ is presented in Fig. 5, curve 1. The high-speed circuit enables various artificial external characteristics $I_a(U_a)$ of the arc furnace to be formed and the corresponding EM optimal control strategies to be implemented.

One of the strategies using a double-loop control system for EM is the stabilization of the current at the level of a set-point value. Such optimal control strategy is implemented by forming an artificial external characteristic $I_a(U_a)$ of the arc furnace by a high-speed electrical circuit with a segment of arc current stabilization $I_a=const$ (Fig. 5, curve 2).

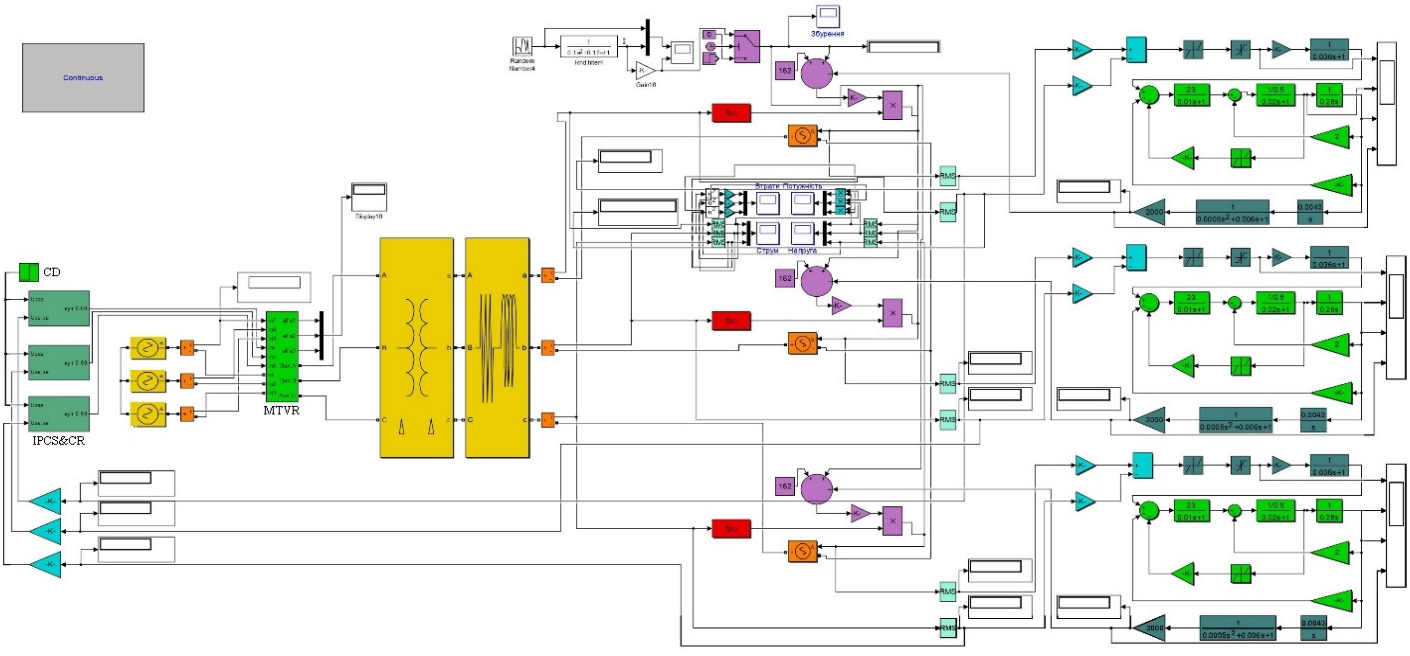

Fig. 2. Block diagram of the three-phase instantaneous coordinates Simulink model of ACS for EM of the DSP-200 furnace

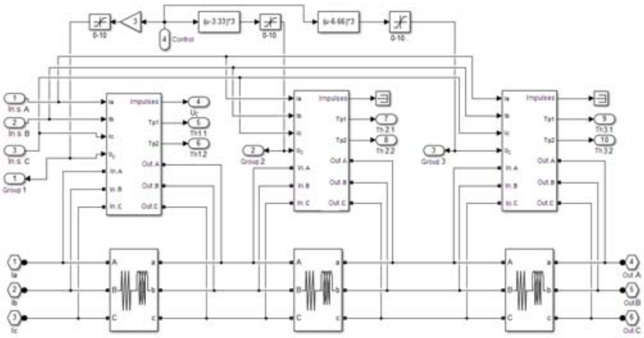

Fig. 3. Simulink-model of magneto-thyristor voltage regulator with three parallel thyristor-reactor groups

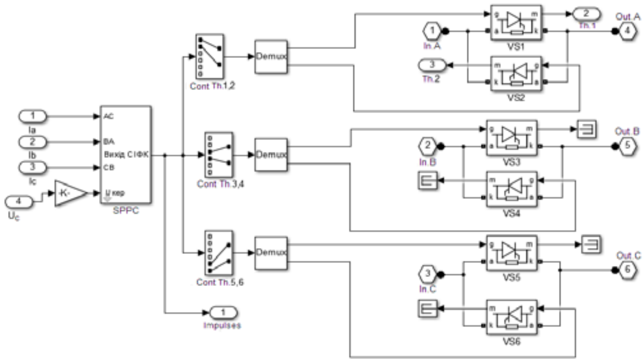

Fig. .4. Simulink model of one parallel TRG with the pulse-phase control system and power thyristors

The use of this strategy leads to in the minimization of arc current dispersion $D_{Ia} \to min$, reduced power loss in the power supply circuit of the furnace, decreased reactive power and its dispersion.

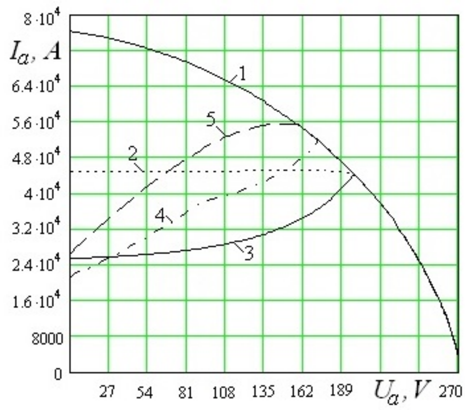

Fig. 5. External characteristics Ia(Ua) of EAF

The regulation law for the inductance of the reactor MTVR for the strategy $D_{Ia} \to min$ is presented as

(1) $$x_p^{I_a}(U_a) = \frac{\sqrt{U_{2f}^2 - U_a^2 - 2rU_a I_{a.st} - r^2 I_{a.st}^2}}{I_{a.st}} - x$$

For the proposed double-loop ACS structure (Fig. 1), other laws of arc current control were devised. As an example, Fig. 5 shows artificial external characteristics 3, 4, 5 of the furnace DSP-200, which correspond to different strategies of EM optimal control: curve 3 presents optimization by the criterion of the reactive power dispersion minimum $Q \to min$, curves 4 and 5 correspond to the multi criteria EM control strategy, whose partial criteria are the arc power maximization (i.e., the furnace output) $P_a \to max$, minimization of the electrical loss power in the power supply circuit of the three-phase arcs (i.e., in the low-voltage circuit of the furnace) $P_{el} \to min$, reactive power dispersion minimization and minimization of the specific losses of electrical power $W \to min$. These partial criteria in the generalized functional of the multi criteria optimization are normalized by the respective weight factors.

The developed Simulink model was used to study the dynamics of EM coordinates' regulation in the structure of the double-loop ACS for the cases of symmetrical and non-symmetrical perturbations of the arc length in the arc spaces, continuous random perturbations with different parameters of stochastic characteristics, as well as to estimate the performance indices when using different laws of control – differential, impedance, as well as one based on the current and voltage deviation laws.

Fig. 6 shows time dependencies of the arc current during implementation of regulation for symmetrical three-phase short circuit using the one-loop EM ACS for control based on the arc current deviation law *a*) for regulation the arc current by the high-speed electrical circuit with the proportionally integral regulator CR of the arc current *b*) and for the case of the functioning of the double-loop EM ACS with the above-mentioned law based on the arc current deviation and PI structure of the arc current regulator CR of the high-speed circuit (Fig. 1). Due to using the high-speed circuit in the ACS, the duration of the arc current regulation is reduced 30-40 times. The insignificant extension of the regulation time in the experiment in Fig. 6,c as compared to Fig. 6,b can be explained by the single-phase symmetry of the elements of the low-voltage circuit of EAF, which is displayed for the control under the arc-deviation law.

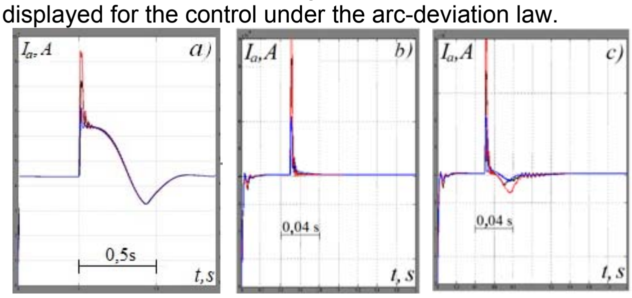

Fig. 6. Time dependencies of the current Ia(t) for regulating the symmetrical short circuit a)by the single-loop ACS with the high-speed circuit b) and by the double-loop ACS for EM control based on the current deviation

Fig. 7 presents similar time dependencies, but for the regulation of non-symmetrical perturbation – short circuit in phase A.

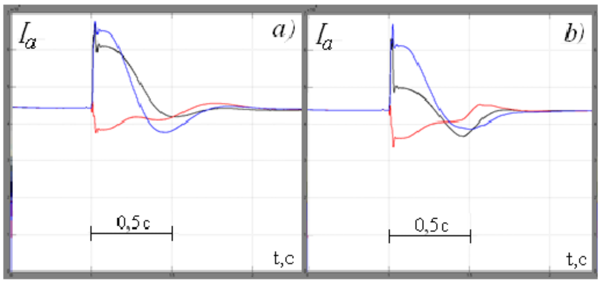

Fig.7. Time dependencies of arc currents for regulating the non-symmetrical short circuit in phase A by the double-loop ACS for different laws of arc length regulation and PI regulator of arc currents of the high-speed circuit

Fig. 8 presents quasi steady-state processes of change of the arc currents $I_a(t)$ for the regulation of random perturbations *f*(*t*) by the double-loop EM ACS (the electromechanical arc power regulator ARDM-T-12 of the furnace DSP-200 and high-speed circuit of arc current regulation (Fig. 1)) at the beginning of the technological stage of solid fusion mixture melting, whereas Fig. 9 shows these same processes $I_a(t)$ at the end of this stage.

The analysis of the dependencies $I_a(t)$ presented in Fig. 8 and Fig. 9 shows quality limitation of the arc current by the value $I_{a.st}$=43.97kA. Due to this, the arc current dispersion is reduced 4-6-times as compared to the operation of the single-loop structure (the power regulator ARDM-T-12).

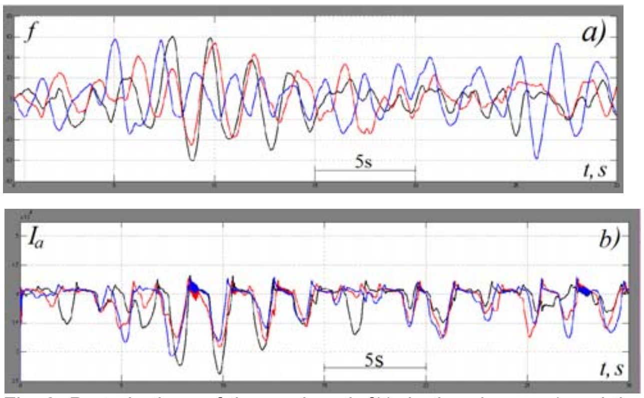

Fig. 8. Perturbations of the arc length f(t) in the phases a) and the respective arc currents Ia(t) b) of the double-loop ACS at the beginning of the solid fusion mixture melting stage

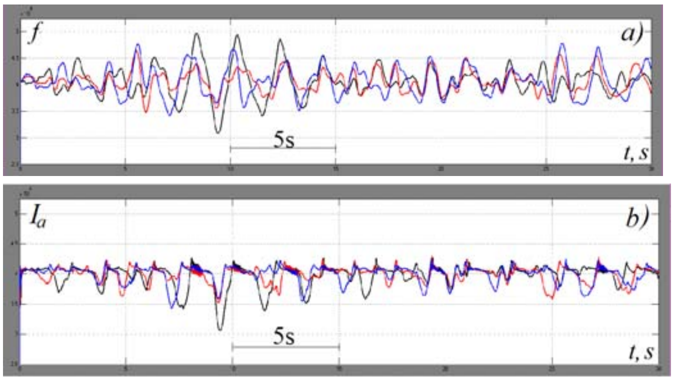

Fig. 9. Perturbations of the arc length f(t) in the phases a) arc currents Ia(t) b) when using the double-loop ACS at the end of the solid fusion mixture melting stage

Reducing dispersion and increasing the speed of arc current control stabilizes the process of reactive power consumption and reduces its average value. At the same time, the power factor increases, power losses in the power supply system and the power circuit of the arc furnace are reduced, as well as deviations, voltage drops and flicker dose are reduced at the point of connection of the EAF to the electrical network.

The developed Simulink model was also used to study the harmonic composition of the arc currents for the operation of different structures of EM ACS, laws of formation of the control signal for electrodes movement and effects of arc length perturbations with various parameters of stochastic perturbations. Fig. 10 presents the diagram of the averaged amplitudes of the characteristic harmonics of the arc currents for the interval of the stochastic arc length perturbation's regulation T=60s by the double-loop EM ACS and formation of the control signal according to the differential law for one TRG (Fig. 10,a) and three parallel TRG (Fig. 10,b) (the first harmonic – 100%, shown in a different scale).

As the harmonics analysis reveals, when using three parallel thyristor-rector groups, the fifth and seventh harmonics are reduced 4-fold, whereas the other harmonics of the arc currents are reduced 1.5-3-fold.

Conclusions

1. A structural three-phase Simulink model in the instantaneous coordinates of the double-loop control system for EM of the electric arc furnace was developed. The model offers a wide range of useful functionalities for computer-aided studies of various structures and for different parameters of EM ACS, different control laws and perturbations' characteristics. It also enables the performance of the online statistical processing of EM coordinates' variation, energy efficiency and electromagnetic compatibility indices, especially the harmonic analysis of the arc current and voltage and power supply network.

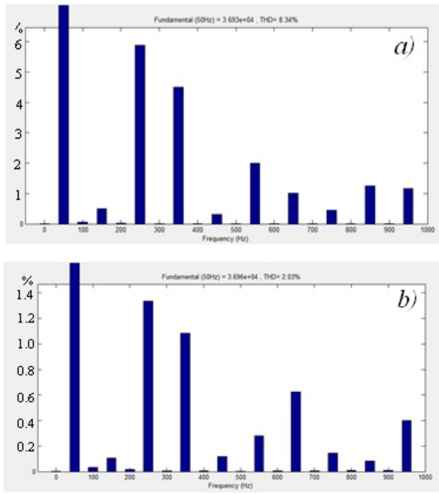

Fig.10. Amplitudes of the arc current harmonics for using one PTRG a) and three PTRG b) in MTVR for the differential control law

2. The results of the study showed a significant comprehensive improvement of the indices of arc current regulation dynamics and the indices of electromagnetic compatibility of the EAF modes and power supply network. It was shown that the functioning of the high-speed circuit of the arc current regulation helped achieve a significant reduction of the arc current dispersion and the level of the higher-order harmonics of the arc currents.

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