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ORIGINAL SCIENTIFIC PAPER

Simulation studies of the electrical mode of an arc-furnace double-circuit control system

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Abstract. The paper presents a structural Simulink model of a double-circuit high-speed automatic control system (ACS) of the electric mode (EM) of an arc steel melting furnace (AF) with a fuzzy control of the arc length. A parametric synthesis is made of the fuzzy model to form an EM mismatch signal based on the Mamdani fuzzy inference system (FIS). Adjustment of the dynamics of the of the basic EM coordinates under at random disturbances is studied. The integral indices of the control quality dynamics of such disturbances during the operation of the proposed EM ACS double-circuit structure and a serial arc power controller of the ARDM-T-12 type are obtained. Integral dynamic indices of the arc voltage and current control, reactive power and power factor are comparatively analyzed. The analysis shows an increase in the dynamic accuracy of stabilization of the EM coordinates, a decrease in reactive power and an increase in the power factor when using the proposed high-speed double-circuit structure of the EM ACS compared to ARDM-T-12 controller.

Keywords: arc steel melting furnace; fuzzy inference system; dynamics; dispersion; energy efficiency

Študija dvokrožnega krmilnega sistema obločne peči

V članku je predstavljen strukturni model Simulink dvokrožnega visokohitrostnega avtomatskega krmiljenja obločne talilne peči z mehkim krmiljenjem dolžine obloka. Izvedli smo parametrično sintezo, ki temelji na Mamdanijevem sistemu mehkega sklepanja. Proučili smo dinamično prilagajanje dinamike v primeru naključnih motenj. Primerjalno smo analizirali integralne dinamične indekse regulacije napetosti in toka obloka, jalove moči in faktorja moči. Analiza potrjuje izboljšano dinamično natančnost stabilizacije, zmanjšanje jalove moči in povečanje faktorja moči pri uporabi predlagane visokohitrostne dvokrožne strukture.

NOMENCLATURE

ACA	arc current adjuster
ACC	arc current controller
ACS	automatic control system
ACS	arc current sensor
AF	arc steel-melting furnace
AVS	arc voltage sensor
CSGU	control signal generation unit
DSGU	displacement signal generation unit
EACCC	electric arc current control circuit
EDEMM	electric drive of the electrode movement mechanism
EM	electric mode
EMC	Electromagnetic compatibility
EMM	electrode movement mechanism
EMALCC	electromechanical arc length control circuit
FIS	fuzzy inference system
FT	furnace transformer
MTVC	magneto-thyristor voltage converter
PPCS	pulse-phase control system
THD	total harmonic distortion

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1 INTRODUCTION

Steel melting in arc furnaces (AF) is characterized by a lower energy cost and a better environmental performance compared to open-hearth furnaces and converter production which at the present stage recede into the background [1]. Approximately a third of the world steel volume is produced using the AF technology, with a trend for a further growth [2], [3]. The advantages of the AF are achievement of the desired temperature mode and the parameters of physicochemical transformations of the charge and melt. In particular, the automatic control system (ACS) of the electric mode (EM) is the determining factor affecting the selection of the AF modes and parameters.

2 ANALYSIS OF THE KNOWN SOLUTIONS

Today, the leading world companies, such as Siemens (SIMETAL system), Danieli (HI-REG and Q-REG+ systems) and others, propose various system engineering solutions for an AF EM ACS. They are based on implementing optimal control of electrical coordinates according to the desired quality criteria [4]-[5]. The used algorithms and EM control models take into account the features and stochastic characteristics of disturbances, phase asymmetry and interconnection, ACS nonlinearity, etc., and implement adaptive optimal control strategies [6]. On the other hand, maximizing the energy efficiency of such control is possible by optimizing the dynamics of electrode movement and in particular by using the principles of the positional control, fuzzy logic and neuro-fuzzy control when coping with electrical regime disturbances. References [7]-[12] proposed some solutions in this direction.

Improving the AF design and melting technologies could increase the energy efficiency and improve the AF electromagnetic compatibility (EMC) indices and power grid modes [13]. It is also possible to increase the speed of the EM coordinates control. This would solve the problem of energy efficiency and EMC of AF and the power grid. A number of circuit and system engineering solutions have been proposed. Some use power control devices, in particular active-reactive power compensators of SVC (static VAY compensator) or STATCOM (static synchronous compensator) [14]-[16].

These devices assure a high-speed control of the EM coordinates, thus reducing voltage deviations and fluctuations, flicker dose, and increasing the power factor. However, they significantly increase total harmonic distortion (THD) of currents and voltages.

The thyristor control of the current limiting reactor in the circuit of the primary winding circuit of the furnace transformer significantly reduces the distortion effect of the sinusoidal form of currents and voltages [20]. Thus, the approach effectively reduces the asymmetry coefficient of phase load and the furnace reactive power, improves the power factor and increases number of environmental indices with a minimal deterioration of THD and the reduction of arc power. These systems have a huge potential in developing new control systems of EM arc furnaces.

Due to the non-stationary interphase disturbing effects, parametric fluctuations, and complexity of the mathematical description, the synthesis of the controlling effects in the complex EM ACS structures of AF requires methods of the theory of fuzzy sets and artificial neural networks [6], [10], [11]. The reference [11] confirm the effectiveness of using models of the fuzzy and neuro-fuzzy control and identification in the context of solving problems of the adaptive optimal control and improving the energy efficiency and EMC.

In this context, it is important to develop solutions for equalizing phase loads, i.e. reducing the level of asymmetry of power grid voltages and arc currents, as well as their THD [18]-[19].

Following the above, a significant increase in the dynamic accuracy of stabilized EM coordinates at the level of set values can be achieved with a high-speed control of the arc currents. This also comprehensively improves the energy efficiency and EMC and increases the phase-to-phase autonomy of the EM coordinate control by optimizing the dynamics of electrode movement while minimizing the effect of EM disturbances and minimizing the THD of the arc currents and voltages.

The purpose of this work is to perform simulation studies of system engineering solutions for automatic control of the AF electric mode based on the concept of adaptive optimal control and high-speed phase-autonomous control of the AF EM coordinates. The solution synthesizing fuzzy model is a two-component vector of the EM coordinate control of a double-circuit AF EM ACS [20].

3 Statement of the Research Problem

The implemented fuzzy adaptive control in combination with the fastest possible implementation of the two-component vector to control the AF electrical coordinates takes into account the conditions of intense non-stationary random phase-asymmetric coordinate and parametric disturbances and the significant complexity of the mathematical description of processes and control with incomplete data about the control object, in particular the burning states of three-phase arcs.

The proposed control strategy is based on a hierarchical double-circuit structure of an AF EM high-speed ACS (Fig. 1). The upper-level system of the hierarchy synthesizes control effects vector $U_{a.set}$, $I_{a.set}$,U_{2ph} for the systems of the lower level according to the selected quality criteria. The lower-level system consists of two control loops: a traditional electromechanical one and a new solely electric one. Both lower-level loops function simultaneously and independently in the control process; they control (stabilize) the arc lengths (voltages) and arc currents, respectively.

By promptly synthesizing the upper level of the hierarchy, the arc lengths (electromechanical circuit) and arc currents (electric circuit) are qualitatively stabilized at an optimal settings level by the lower-level circuits. The qualitative stabilization of the EM coordinates further increases the efficiency of the optimal control strategy according to the desired quality criterion. The tasks solved by these circuits are equally important.

The electromechanical arc length control circuit (EMALCC) (Fig. 1) consists of: an arc current sensor (ACS), arc voltage sensor (AVS), displacement signal generation unit (DSGU), control signal generation unit (CSGU) for electrode movement, electric drive of electrode movement mechanism (EDEMM) and electrode movement mechanism itself (EMM).

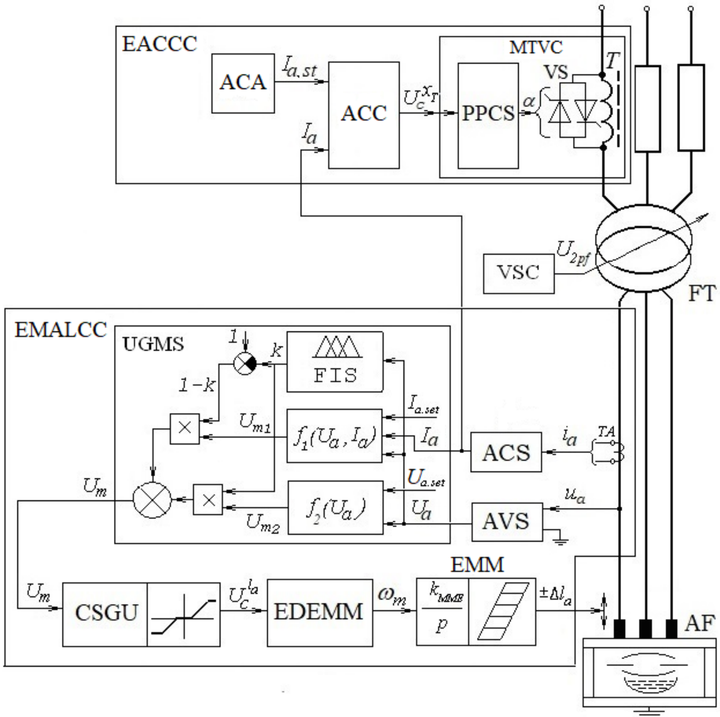

Figure 1. Functional block diagram of an AF EM high-speed ACS with a two-component fuzzy-control vector.

The electric arc current control circuit (EACCC) consists of a magneto-thyristor voltage converter (MTVC), arc current controller (ACC) and arc current adjuster (ACA). MTVC consists of a reactor (T), thyristors (VS) and pulse-phase control system (PPCS). The voltage step switching circuit (VSC) of the furnace transformer (FT) sets the required step of the secondary phase voltage U_{2ph}.

The fuzzy model of the EM mismatch signal $U_m(t)$ (a distinctive functional feature of the proposed EMALRC structure) is based on two partial laws: a modified differential control law:

$$U_{m1}(U_a, I_a) = f_1(U_a, I_a) = a \cdot U_a - b \cdot (I_a - I_{a.set}), \quad (1)$$

and an arc voltage deviation control law:

$$U_{m2}(U_a) = f_2(U_a) = k_u \cdot (U_a - U_{a.set}), \quad (2)$$

where U_a and I_a are the current average values of the voltage and arc current;

$U_{a.set}$ and $I_{a.set}$ are the ER ACS settings according to the arc voltage and current, respectively;

a, b and k_u are constant coefficients determining the given EM.

The smooth switching between partial laws (1) and (2) is implemented by synthesizing a model of the fuzzy inference system (FIS). Using FIS, weighting coefficients k and $(1-k)$ of laws $f_2(U_a)$ and $f_1(U_a, I_a)$ are formed in arc voltage change function U_a (Fig. 1), resulting in a mismatch signal formed at the UGMS output:

$$U_m(U_a, I_a) = k \cdot f_2(U_a) + (1-k) \cdot f_1(U_a, I_a), \quad (3)$$

in the CSGU function producing control signal $U_c^{l_a}$, used to move the electrode.

During the short circuits or arc breaks and close to them, they are characterized by a significant EM deviations. The modified differential law (1) is thus used, while the law (2) is according to the deviation of the arc voltage used in the regimes close to the given one.

The FIS input linguistic variable is the arc voltage U_a. Membership functions of input linguistic variable U_a are depicted in Fig. 2.

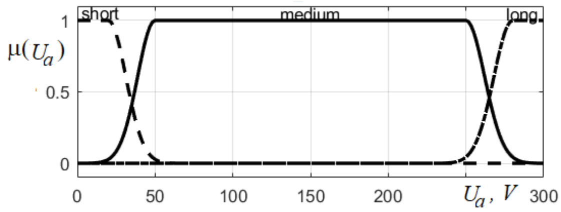

Figure 2. Membership functions of the linguistic variable of the blocks FIS.

In the Mamdani FIS, the following fuzzy rule base is implemented for the change in the mismatch formation model adaptive to the burning states:

1. if $U_a \in$ short then $k = 0$ [1] ;
2. if $U_a \in$ medium then $k = 1$ [1]; (4)
3. if $U_a \in$ long then $k = 0$ [1].

The obtained FIS input/output dependence is shown in Fig. 3.

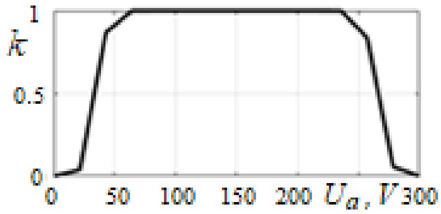

Figure 3. Dependences $k(U_a)$ of FIS.

The EACCC arc current control is implemented by the corresponding control of the equivalent inductive resistance of reactor T of the magneto-thyristor voltage converter MTVS as a function of the deviation of current I_a from given value $I_{a.set}$. These signals are formed at the outputs of the ACS sensor and the arc current adjuster ACA, respectively, in each phase of AF EM ACS. Control signal U_c^{xT} for changing the equivalent resistance of reactor T is formed by the proportional-plus-integral arc current controller ACC with the below transfer function

$$W_{ACR}(s) = \frac{T_1 \cdot s + 1}{T_2}, \quad (5)$$

where T_1 and T_2 are the coefficients of the ACR PI controller corresponding to the adjustment of the EACRC dynamics to the technical optimum.

The proposed hierarchical double-circuit high-speed ACS structure utilizes the controlling effects of the control circuits, which are $\pm\Delta l_a$ at the movement of the electrodes in EMALCC and $-U_c^{xT}$ at the change in the equivalent inductive reactance of reactor T in EACCC, which continuously changes in the process of working out the EM disturbances. Their action stabilizes the lengths and currents of arcs at the level corresponding to the given EM.

An optimal control of the hierarchical ACS changes discretely and is implemented for each technological melting stage in accordance with the melting schedule of a certain type of steel or alloy. They are formed at the highest level of the ACS hierarchy: U_{2ph}, $U_{a.set}$ and $I_{a.set}$, the stage of the secondary voltage of the furnace transformer FT stage and the settings of the arc voltage and current, respectively.

The dynamics of the double-circuit AF EM ACS structure is studied by using a computer Simulink model adapted to the parameters of an arc steel melting furnace of DSP-200 type [21]. Our simulations provided the basis for a comparative analysis of the dynamic indices of the proposed ACS double-circuit structure (Fig. 1) using a fuzzy model synthesizing EM mismatch signal U_m (3) and indices of the EM ACS dynamics based on the ARDM-T-12 series arc power controller used in the DSP-200 furnace (EM single-circuit ACS functioning according to the differential model (1)).

The AF consumption mode of a reactive power $Q(t)$ decisively affects the indices of the energy efficiency and EMC. The $Q(t)$ processes obtained on the Simulink model include the reactive power at the first harmonic of the load voltage and the current and distortion power caused by their higher harmonics.

The time dependences of the EM coordinates obtained with the Simulink model at random disturbances according to arc lengths $l_{a_j}(t)$ with stochastic characteristics corresponding to the technological stage of melting wells in the charge during the operation of the proposed AF EM double-circuit high-speed ACS of DSP-200 type (Fig. 1) with the fuzzy law (3) of the formation of the EM mismatch signal are shown in Fig. 4 (30-second fragments), in particular, voltages $U_{a_j}(t)$, currents $I_{a_j}(t)$ of the arcs, reactive powers $Q_j(t)$ and power factors $\cos\varphi_j(t)$ at disturbances $l_{a_j}(t)$ $(j = A, B, C)$.

The stationarity interval of changes in the perturbations of the DSP-200 furnace at different melting stages is $T \in [80, 120]$ s. During these intervals, their dynamics is studied and their indices are calculated.

Fig. 5 shows the similar time dependencies of changed EM coordinates $U_{a_j}(t)$, $I_{a_j}(t)$, $Q_j(t)$ $\cos\varphi_j(t)$ at the same disturbances at arc lengths $l_{a_j}(t)$ in the phases of the DSP-200 furnace during the operation of the arc power controller ARDM-T-12 series.

Table 1 shows the static analysis of the simulated time dependences of the changes in the EM coordinates (Figs. 4 and 5)—indices of dynamics and EMC, for both investigated structures of the EM ACS of the DSP-200 furnace by means of the phase-averaged values of voltages $\overline{U}_a$, currents $\overline{I}_a$, reactive power of the arc furnace $\overline{Q}$ and power factor $\overline{\cos\varphi}$, as well as their dispersions $\overline{D}_{U_a}$, $\overline{D}_{I_a}$, $\overline{D}_Q$, and $\overline{D}_{\cos\varphi}$.

Table 1. Dynamics indices of the studied structures of EM ACS of the DSP-200 furnace.

Quality indices \ **ACS structure**	**Double-circuit high-speed ACS with FIS**	**Single-circuit ACS (ARDM-T-12 controller)**
Arc voltages, $\overline{U}_a$, V	199.2	206.9
Dispersion of arc voltages, $\overline{D}_{U_a}$, V2	1528	2084
Ars currents, $\overline{I}_a$, kA	38.77	40.23
Dispersion of arc currents, $\overline{D}_{I_a}$, kA2	11.72	48.46
Reactive power of AF, $\overline{Q}$, MVAr	12.26	13.11
Dispersion of reactive power of AF, $\overline{D}_Q$, MVAr2	1.986	7.043
Power factor, $\overline{\cos\varphi}$	0.629	0.508
Disperion of power factor, $\overline{D}_{\cos\varphi}$	0.011	0.022

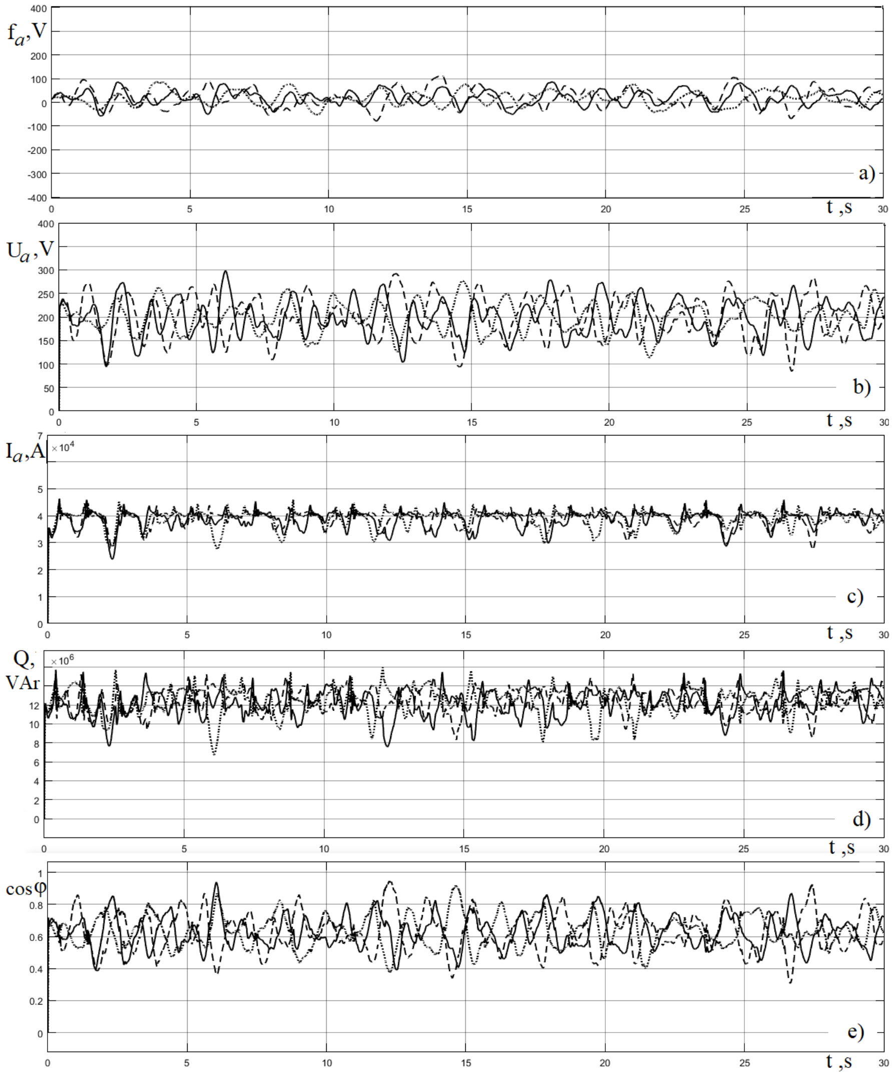

Figure 4. Time dependences (30-second fragments) of the EM coordinates when adjusting disturbances $l_{a_j}(t)$ using an EM double-circuit ACS of the AF DSP-200 type (Fig. 1).

Based on the results of the analysis of the obtained quality indices of the dynamics and statics of the control of random disturbances at the stage of well penetration shows that using the proposed double-circuit high-speed EM ACS with a fuzzy law (3) of the formation of the displacement signal compared to the indices of a single-circuit ACS based on a series arc power controller ARDMT-12 of the DSP-200 furnace improves the values of each variable.

Dispersion of the arc currents decreases 4.2 times during the operation of a double-circuit ACS with a fuzzy law of formation of the mismatch signal (3) compared to the operation of the ARDM-T-12 controller. Likewise, the reactive power, the power of the arc furnace decreases by 6.5%, and its dispersion 3.5 times. The power factor increases by 24%, and its dispersion is reduced twice.

The mode of electrical transformation in arc gaps both in time and in arc space is stabilized due to the reduced dispersion of the arc voltages and currents. Local overheating of the melt is eliminated and the phase thermal asymmetry of its heating is reduced. Moreover, a positive effect on reducing the fluctuation of the power grid voltage and flicker value is obtained due to the stabilization of the arc power.

It should also be noted that decrease in the installed power of the filter-compensating devices and the dynamic compensation are due to the decrease in the reactive power and stabilization of its consumption mode. In addition, the decrease in the reactive power and stabilization of its consumption minimizes deviations and fluctuations of the power grid voltage and also the flicker value.

The increase in the AF productivity and reduced electricity consumption are due to the reduced arc current dispersion. Such estimates for single-circuit structures of AF EM ACS are obtained using the nomograms given in [22].

In addition, the increased dynamic accuracy of the arc current stabilization positively affects the AF EMC indices and the power grid modes, i.e., fluctuations and

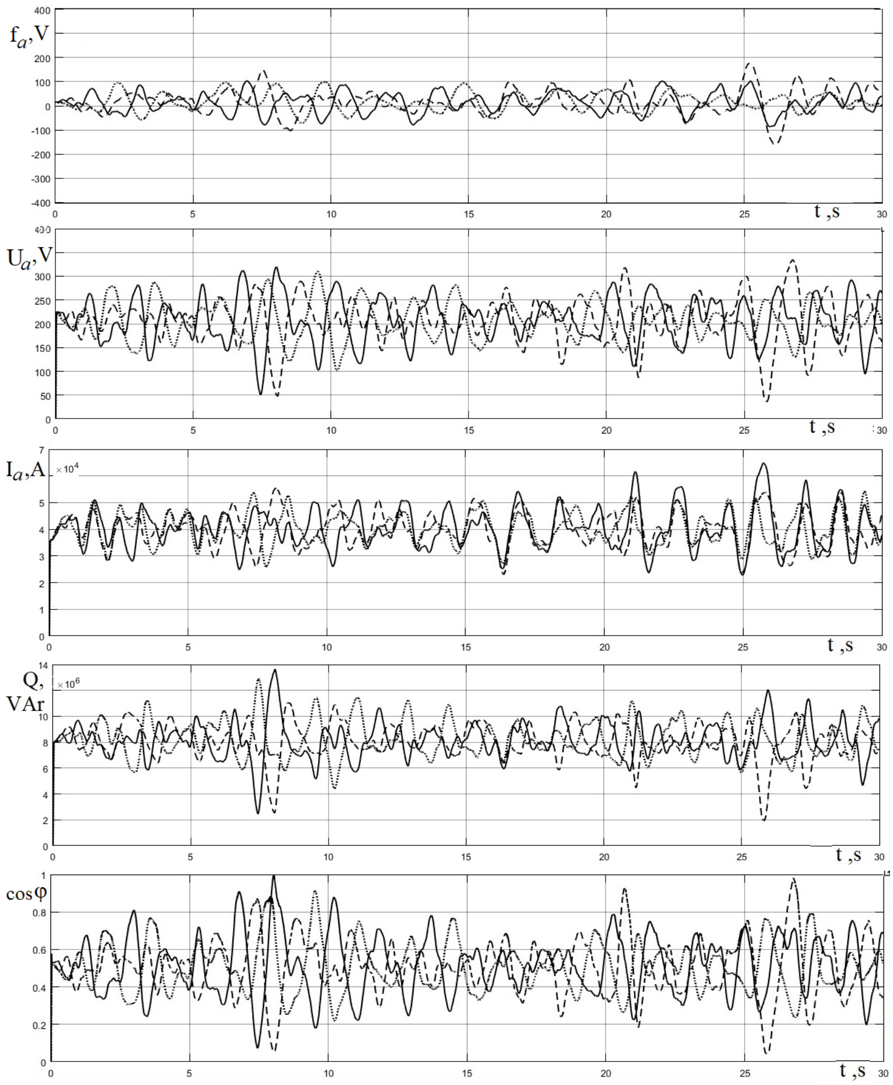

Figure 5. Time dependences (30-second fragments) of EM coordinates when controlling disturbances $l_{a_j}(t)$ using the ARDM-T-12 controller of the DSP-200 furnace.

deviations of the network voltage, flicker value and power factor.

An appropriate control effects U_{2pf} , $I_{a.set}$ and $U_{a.set}$ of the upper level of the proposed EM double-circuit ACS provides an optimal solution for a comprehensive improvement of the AF productivity, reduces the specific electricity consumption and the reactive power, increases the power factor and improves a number of other EMC indices.

4 Conclusions

The paper presents results of a Simulink study of a double-circuit structure of an EM ACS of an arc steel-melting furnace based on a fuzzy law of formation of a mismatch signal and a high-speed electric circuit to control the furnace arc currents. A high-speed control of random EM disturbances is assured. Compared to the serial arc power controller of the ARDM-T-12 type, the dynamic accuracy of stabilization of the EM coordinates and indices of the energy efficiency and EMC increase.

The Simulink studies show a decrease in the dispersion of the EM coordinates resulting in an increase in the productivity of the arc furnace and a decrease in the specific energy consumption and an improvement in the energy efficiency and in EMC.

The proposed fuzzy law (3) of the formation of the mismatch signal allows an increase in the phase-by-phase autonomy of the disturbance control resulting in a decrease in the dispersion of the EM coordinates and increase in the phase-by-phase symmetry of electrical and temperature coordinates. Following the above, an improvement should be made of a number of the EMC and environmental indices, in particular, indices of toxic air emissions.

In our future research, the quality of the mode symmetrization and electric energy indices on the power supply buses of the electric furnace will be estimated based on the proposed solutions.

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