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MULTICRITERION INTELLIGENT CONTROL SYSTEM AND OPTIMAL STABILIZATION OF ARC STEEL-MELTING FURNACE ELECTRICAL REGIMES COORDINATES

Orest Lozynskyi, Roman Paranchuk, Yaroslav Paranchuk

Lviv Polytechnic National University

lozynsky@polynet.lviv.ua, yparanchuk@yahoo.com

Abstract. A hierarchical structure of an adaptive multicriterion modes control system in a three-phase arc steel furnace has been proposed. Models of synthesis of an optimal control vector have been developed. Adaptation of control and optimal stabilization has been performed depending on technological stages, which are identified by a neural network.

Keywords: arc steel-melting furnace, neural network, control system.

1. Introduction

Contemporary state of metal production industry is characterized by continuous growth of part of steels melted in three-phase electric arc furnaces (EAF). These steel-melting installments are characterized by large steady-state power of furnace transformer up to 1 MV·A/ton. They are characterized by highly dynamic, nonlinear and non-symmetrical load. The arc furnaces' functioning also is accompanied by technological short circuits and unstable, discontinuous burning of arcs and it can lead to oscillations of arc power, which are commensurable with furnace transformer power. Moreover, furnace functioning leads to oscillations, nonlinear shape distortions and non-symmetry in power system voltage. Four important problems arose while exploiting arc furnaces:

1. Ensuring maximum arc power while melting of solid charge.
2. Qualitative stabilization of arc power.
3. Minimization of specific power losses.
4. Limiting nonlinear and varying load impact on a power system.

The abovementioned problems significantly increased in high-power and high-impedance furnaces with arc voltages of 1000-1500 Volts and specific power of 1 MV·A/ton. In general, these problems are contradictory and can be solved only with toleration of some compromises.

Solution of the mentioned task requires adequate improvements of melting technology, development of new efficient melting systems and also creation of hierarchical intelligent systems of adaptive optimal control and high-speed multi-circuit systems for electric regime coordinates control. Moreover, high arc current amplitude oscillations lead to vibrations and significant electrodynamic forces in the windings of electrical power equipment, which decreases its functional reliability and life time. This is mainly caused by the low dynamic accuracy of controlling the electrical-regime parameters because of the significant sluggishness of existing electromechanical (electrohydraulic) electrode-position control systems.

Nowadays, the part of electrical steels in the total steel output is increasing, the power of an electric furnace is increasing, and, as the result, melting process is intensified [1, 2]. Therefore, it is important to improve the electrical and technical efficiency of arc furnaces and the electromagnetic compatibility of the electrical-regime parameters with the power system parameters.

As for the technical and economic assessment, the optimum control of electric melting is known to be two to three times as efficient as the solutions intended for stabilizing electrical regime parameters [3]. Nevertheless, those problems should be solved concurrently, since the qualitative stabilization of electrical-regime parameters at the level of synthesized optimum values additionally increases the control efficiency. Therefore, the main methods of increasing the electrical and technical efficiency of melting in arc steel furnaces are represented by developing control circuits and synthesis of optimal control methods. They are intended for minimization of dispersion of the electrical regime coordinates and their stabilization them at the level of synthesized optimum values.

2. Analysis of known solutions

The functions of most existing EAF electrical-regime control systems (e.g., ARDG, ARDMT, RMM, and STU arc-power controllers) are mainly limited to the maintenance of a specified phase impedance, arc voltage, or arc current depending on the voltage of the secondary winding of a furnace transformer (FT). As noted above, high oscillations in the electrical-regime parameters, which are caused by the low dynamic accuracy of their control and the limited functional optimization abilities of the above mentioned controllers, do not allow one to substantially increase the efficiency of the EAF heat-regime control.

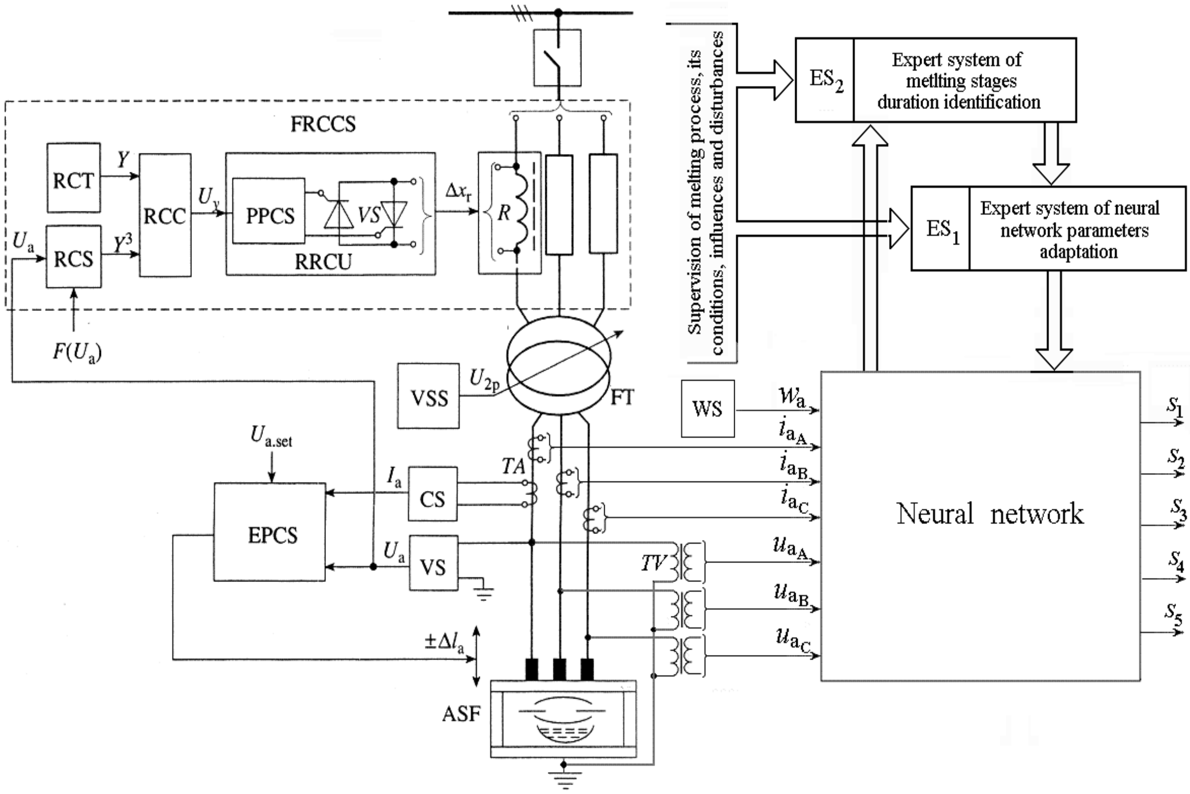

Fig. 1. Functional schematic diagram of the power and electrical-regime control system for an EAF with neural-network-based melting stages recognition: FRCCS is the regime coordinate control subsystem; RCS and RCT, regime coordinate set-point device and transducer, respectively; RCC, regime coordinate controller; RRCU, reactor-resistance control unit; PPCS, pulse-phase control system; VS, thyristor unit; R, reactor; EPCS, electrode-position control subsystem; CS and VS, current and phase-voltage sensors, respectively; FT, furnace transformer; and VSS, transformer voltage step switch; ES1 and ES2, expert systems

To improve the electromagnetic compatibility of the arc-furnace electrical operating conditions with the power system conditions, static filter-compensating devices are widely used in metallurgy, which should compensate for the negative effects of a furnace on the power system. Of course, such solutions are often required. But we believe that metallurgists should mainly obtain automatic and algorithmic solutions intended for the suppression of the causes of disturbances in their origin (in the power circuit of an arc furnace), i.e. solutions intended to anticipate the appearance of negative actions on the technical and economic indices of the furnace and the electromagnetic compatibility of the furnace electrical operating conditions with the power system conditions.

The authors of [4] give an example of the realization of this direction in increasing the efficiency of controlling the EAF electrical conditions; they describe an EAF power system that includes a saturating reactor. In furnaces with such a power system and high impedance, metallurgists can increase the EAF transformer power via increasing the secondary voltage and can run a heat using long arcs. These solutions can decrease the arc-current dispersion, increase the arc stability, and decrease the short-circuit probability, all other things being equal.

However, when the method of controlling the reactor resistance proposed in [4] is used, a single type of artificial external characteristics (AECs) in a furnace, i.e. arc current-voltage characteristics ($I_a(U_a)$), is only realized. This type is represented by characteristics such that the arc currents are stabilized in the range of low and medium arc voltages (short and long arcs). The arc current is a controlled parameter in such furnace AECs at a given voltage step of a furnace transformer, and the arc current is specified by the bias current of the saturating reactor. This scheme restricts the functional possibilities of the system in the realization of various optimum strategies of controlling EAF regimes using partial criteria or generalized target functionals, which are formed with allowance for current heat conditions and current requirements for the technical and economic indices of an arc furnace. Moreover, the realization of this control requires a significant preset power of the saturating reactor, and the shape of the electric current during control is close to a rectangular shape. The fabrication of such a saturating reactor requires high-quality magnetic materials with oriented crystals.

3. Two-circuit high-speed control system

To implement these directions in increasing the control efficiency, we propose a two-circuit coordinate-parameter hierarchical automatic control system (CS) for an EAF electrical regime with automatic neural network based identification of technologic stages (Fig. 1).

In this two-circuit system, regime coordinates, i.e., electrical regime coordinates such as the arc current, arc power, and furnace reactive power (which change according to their specific laws), are rapidly controlled and stabilized at a given level using the thyristor-assisted control of the resistance of a reactor located in the primary winding circuit of the furnace transformer. Conventional single-phase current-limiting unsaturated reactors, which do not require special magnetic materials for their magnetic system, are used as the reactor in each furnace-power phase.

This CS of melting modes consists of two subsystems (control circuits), namely, an electrode position control subsystem (EPCS) and a furnace-regime coordinate-control subsystem (FRCCS). These systems operate simultaneously and independently and have isolated phases.

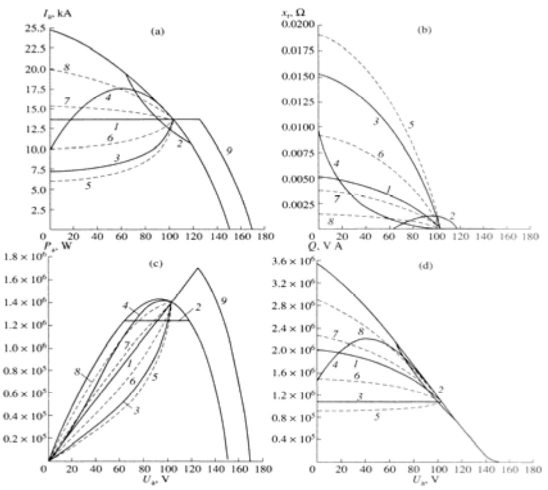

Fig. 2. Electrical characteristics of a DSP-6 arc steelmaking furnace with a two-circuit electrical-regime control system (the numerals on the curves are explained in the text

The first subsystem is an ordinary electrode-position control system with an electromechanical or hydraulic actuator, which controls the change in the arc length $\pm\Delta l_a$. The control of the arc length is indirectly realized as a function of the current values of arc current I_a and voltage U_a, and the signals proportional to these values are generated at the output of an arc current or voltage sensor, respectively. An arc-voltage setting signal $U_{a.set}$, which is proportional to l_a, is the master control of this subsystem. If necessary, transformer voltage steps can be switched using VSS devices.

The FRCCS subsystem is intended for controlling a furnace-regime coordinate (electrical-regime parameter), such as the arc current, arc power, or furnace-reactive power.

A change in the reactor resistance Δx_r is the master control of this subsystem. In each phase, this change is controlled smoothly and continuously via shunting the reactor by a VS thyristor unit in a certain controlled segment of a powering voltage half-cycle. The segment time is determined by the phase of the output signal of a pulse-phase control system (PPCS), and this signal, in turn, forms as an autocorrelation function of the output signal U_y of a proportional-integral furnace regime coordinate controller (RCC). The input of this controller receives Y^3 signals from a set-point device and Y signals from the sensor of a certain controlled furnace-regime coordinate. In the general case, the setting signal Y^3 of this subsystem is a function of the arc voltage, which enters into the input of a furnace-regime coordinate set-point device (RCS). In particular, upon the stabilization of a regime coordinate, signal Y^3 is a constant, which determines the required level of regime-coordinate stabilization. In the general case, setting signal Y^3 is calculated in the RCS from a $Y^3 = F(U_a)$ relation, which is the setting action of this subsystem (this is especially effective for the realization of the adaptive multicriterion control of an EAF electrical-heat regime). Compared to the electromechanical EPCS subsystem, the speed of this subsystem is higher by an order of magnitude: its response time is 0.03-0.04 s. For the reactor resistance to be controlled with a thyristor, metallurgists developed solutions so that the distortion of the sinusoidal furnace-loading currents is minimal.

4. Melting stages recognition system

One of the prerequisites of guaranteed production of steels and alloys with desired physical and chemical properties and of high technological and economical efficiency during melting process is synthesis and implementation of two-circuit system control vector depending on technological melting stage. Therefore one of main problems is recognition of technological melting stages and moments of their changes

Most efficient approach to technological stages recognition under conditions of insufficient information about technological process and its stochastic fluctuations is recognition based on neural networks principles. For implementation of such approach, three-layer neural-network- based expert system is included into control system. It is used for recognition of melting stages S_1, S_2, …, S_5 (Fig.1). Input information of the neural network is vector of instantaneous values of arc voltages u_{aA}, u_{aB}, u_{aC}, currents i_{aA}, i_{aB}, i_{aC} and consumed on current stage active energy w_a [5,6]. Informative parameters of mentioned electrical mode coordinates time dependences are averaged values on stationarity intervals of their canonical harmonics (they are calculated using FFT method). Also, power spectrums of voltages U_a and currents I_a in informative frequency range are taken into account. They are calculated using the fast wavelet transform technique. Dispersion, correlation coefficient and total harmonic distortions (THD) coefficients of currents and voltages are used too. Algorithm of operative calculation of mentioned parameters integral values is implemented using microprocessor device. Optimal parameters of three-layer neural network used for melting stages recognition were obtained, training and testing performed. Industrial testing of network was performed on arc furnace DSP-3. This neural network forms the first level of melting stages recognition hierarchical system.

At the second level there is an expert system ES_1, which serves for adaptive optimization of neural network variable coefficients (coefficients of synaptic relations). This expert system is of production type, in other words is it based on "instructive knowledge" – in form of production rules "If … Then …" This expert system, basing on expert knowledge and operative input information, performs discrete parametric optimization of neural network to parameters of furnace charge. It loads from database synthesized matrix of synaptic relations, which corresponds to current type, density and stowing of hard charge, changes transfer constant of active energy measuring channel proportionally to the weight and temperature of loaded charge. Knowledge base of expert system is assembled from formalized technical specialists' experience.

At the third, highest level of hierarchy expert system ES_2 is used, which processes expert knowledge from exact analysis of melting stages changes. If identification error is greater then certain threshold, ES_2 initializes procedure of learning (adjusting) to slowly varying conditions of melting process: current state of furnace cladding, power supply parameters, external temperature, etc.

The developed expert hierarchical neural-network-based system for melting stages recognition naturally combines advantages of neural networks and expert systems. Neural networks have capability of operative parametrical adaptation and expert systems make it possible to relatively simple identify moments of adaptation algorithms start.

This ensures small error of melting stage change moments identification. The error didn't exceed 5% during experiment melting in DSP-3 furnace.

5. Electrical characteristics of a two-circuit CS

Fig. 2a shows the natural and artificial external characteristics of a DSP-6 arc furnace in the first step of the furnace transformer. Artificial external $I_a(U_a)$ characteristics *7*, *2*, and *3* are formed by the two-circuit coordinate-parameter control system upon the stabilization of the arc current, arc power, and furnace reactive power in the zone of short and medium arc lengths. Fig. 2b shows the corresponding reactor resistance $x_r(U_a)$ curves for characteristics *1*, *2*, and *3*. Fig. 2c and 2d show the artificial characteristics of the arc power ($P_a(U_a)$) and furnace reactive power ($Q(U_a)$) corresponding to characteristics *1*, *2*, and *3*. For the artificial furnace characteristics corresponding to characteristics *1* and *2*, we have obtained the following $x_r(U_a)$ dependences for controlling the reactor resistance:

$$x_r^I(U_a) = \frac{\sqrt{U_{2p}^2 - U_a^2 - 2rU_a I_{as} - r^2 I_{as}^2}}{I_{as}} - x\,;$$

$$x_r^P(U_a) = \frac{\sqrt{U_a^2 - (U_{2p}^2 - U_a^2 - 2rP_{as}) - r^2 P_{as}^2}}{P_{as}} - x\,;$$

where:

U_{2p} – secondary-phase voltage of the electric-furnace transformer;

r and x – active and reactive current-lead resistances, respectively;

I_{as} and P_{as} – levels of arc-current stabilization and arc-power stabilization, respectively.

The problem of coordinate stabilization during regime optimization is a partial problem. In the general case, the proposed two-circuit CS can realize other $I_a(U_a)$ AECs, e.g., those of type *4* (Fig. 2) or similar to the family of dashed curves *5*,*6*,*7* and *8*. For these and related AECs, we obtained models for the calculation of the corresponding reactor resistances $x_r^Y(U_a)$.

In the general case, we take into account a synthesized $x_r(U_a)$ dependence and calculate the artificial external characteristics of a furnace using the expression

$$I_a(U_a) = \frac{-U_a r + \sqrt{(rU_a)^2 + (r^2 + (x + x_r(U_a))^2)(U_{2p}^2 - U_a^2)}}{r^2 + (x + x_r(U_a))^2}. \quad (1)$$

In particular, AECs of types *1*, *3*, *5*, *6*, *7*, or *8* (Fig. 2) are calculated from (1) via multiplying a forming coefficient γ from the basic regulation law $x_r(U_a) = \gamma\, x_r^b(U_a)$. The basic regulation law is taken to be a $x_r(U_a)$ law corresponding to characteristics *1* or *3*. We have assumed that the basic regulation law corresponds to characteristic *3*, i.e., $x_r(U_a) = x_r^Q(U_a) = x_r^b(U_a)$, where γ=1. When substituting $x_r(U_a) = \gamma\, x_r^b(U_a)$ into (1) and changing the values of γ in the range from 0 to 1.25, we calculate the family of characteristics *8*, *7*, *1*, *6*, *3*, and *5* located between the natural external furnace characteristic (γ = 0) and AECs of type *5* (γ = 1.25).

When AECs are formed via adjusting the reactor resistance, the arc power $P_a(U_a)$ decreases with respect to the power for the natural characteristic ($x_r(U_a) = 0$). To compensate for this decrease and to increase (if necessary) the average arc power, it is sufficient to increase the secondary voltage of the furnace transformer (Fig. 2, characteristic 9) by 10-30%, which corresponds to modern trends in the intensification of the regimes of high-impedance long-arc furnaces [1, 2].

In the general case, the control vector $\vec{x}(U_{2p}, U_{a\cdot set}, \gamma_1, \gamma_2, ...)$ contains the secondary voltage of the furnace transformer U_{2p}; the arc-voltage setting $U_{a\cdot set}$ of the electrode-position controller; and the coefficients γ_1, γ_2, ... of an analytical expression for the AECs of the arc furnace (which are variable parameters for optimum control synthesis).

6. Optimal control synthesis models for CS

We now determine the family of particular optimum criteria and compose a control target functional for the entire system in order to perform the operative synthesis of the optimum control of an EAF electrical regime according to current (technological, industrial, energetic, etc.) external conditions and the required technical and economic indices.

One of the versions of the mathematical optimization model is a multicriterion multiparametric optimization based on the set of alternative Pareto's optimum solutions,

$$\Phi(\vec{x}) = \Phi(Q_1(\vec{x}), Q_2(\vec{x}), ..., Q_s(\vec{x})) = \sum_{i=1}^{s} \lambda_i Q_i(\vec{x}) \Rightarrow \min,$$

where:

$Q_1(\vec{x}), Q_2(\vec{x}), ..., \; Q_s(\vec{x})$ – partial criteria;

λ_i – their weight coefficients.

This functional determines a control target and, along with the vector $\vec{x}$ of variable setting system actions and the description of its variation range $\vec{x} \in D$, forms a mathematical model for decision making in the problem of the optimum multicriterion control strategy.

One of the challenges in increasing the level of the electromagnetic compatibility is the synthesis of optimum control based on an indirect criterion, namely, the sum of the dispersions of the normalized arc current $D^*_{I_a}(U_{a.set}, \gamma)$ and the furnace reactive power $D^*_Q(U_{a.set}, \gamma)$. The extremum of this criterion corresponds to the minimum of the dispersion of the network voltage fluctuational component,

$$D^*(U_{a.set}, \gamma) = \lambda_{I_a} D^*_{I_a}(U_{a.set}, \gamma) + \lambda_Q D^*_Q(U_{a.set}, \gamma) \Rightarrow \min, \quad (2)$$

where:

λ_{I_a} and λ_Q – weight coefficients of the $D^*_{I_a}$ and D^*_Q dispersions, respectively.

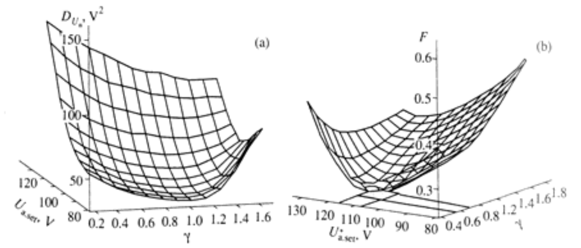

Fig. 3. Dependences of (a) the network-voltage dispersion and (b) the value of functional (3) on the setting actions of the two-circuit electrical-regime control system of a DSP-6 furnace

Fig. 3a shows the dependence of the network voltage dispersion D_{U_a} on the variable setting actions of the system, namely, the EPCS arc-voltage setting and the AEC forming coefficient γ, which is obtained when the DSP-6 furnace regime is controlled by functional (2). The coordinates of its minimum determine the optimum setting actions $U^*_{a.set}$ and γ^* of the two-circuit system when the electrical regime of the arc furnace is controlled by functional (2).

Another approach is the optimum-compromise control using the criterion of the maximum electric-power efficiency. This approach is effective due to the modern conditions of deficient and expensive electric power and the tendency toward intensifying a heat via an increase in the furnace transformer specific power (i.e., an increase in the secondary voltage of the transformer). This control can be synthesized using, e.g., the generalized additive functional

$$\begin{aligned}\Phi(U_{a.set}, \gamma) = 0.28(1 - \overline{P}^*_a(U_{a.set}, \gamma) + \\ + 0.24\overline{P}^*_{ep}(U_{a.set}, \gamma) + 0.21 D^*_{I_a}(U_{a.set}, \gamma) + \\ + 0.27\overline{W}^*(U_{a.set}, \gamma)) \Rightarrow \min\end{aligned} \quad (3)$$

Fig. 3b shows the surface of this functional, and its extremum coordinates $U^*_{a.set}$, γ^* correspond to the setting actions of the system when the optimum control is realized according to the maximum efficiency of using electric power.

Control synthesis based on the formation of arc-furnace AECs of type *4* in Fig. 2 is an effective approach to optimizing furnace regimes according to the criterion of the maximum electric-power efficiency. A positive specific feature of characteristics of this type for this criterion is a minimum decrease in the arc power for medium-length arcs (in the range of rational furnace regimes) and an effective decrease in the power of the electric loss and the reactive furnace power for short arcs (for operational short circuits and similar regimes). As a result, the specific electric power consumption decreases, the reactive power consumption decreases, and the electric efficiency of an arc furnace increases.

7. System of adaptive optimal stabilization of electrical mode coordinates

To obtain maximum technologic efficiency from usage of the described strategies of multicriteria optimal control of melting regimes it is necessary to implement a high-quality stabilization of electric mode coordinates at level of optimal synthesized settings of the electrodes moving system. Solving this problem is complicated by the influence of intensive non-stationary random disturbances in the arc gap and parametric perturbations in a power circuit of arc furnace. Particularly, crucial impact on the deterioration of arc furnace performance is caused by arc length fluctuations, changes of voltage gradient in arc intervals, changes of the short network elements parameters, including dependence of the dynamic volt-ampere characteristics of arcs, fluctuations and deviations of voltage in power network. These factors lead to changes in current dispersion, fluctuations of voltage in power network and to higher harmonics in arc currents. The result is a change of coordinates of extremum of the generalized functional and partial control quality criteria, including the coordinates of extremum of maximum arc power, specific consumption of lectricity, cost of ton of smelted steel, furnace efficiency, etc.

Taking non-steady nature of the above mentioned disturbances into account, it is appropriate to implement quick parametric adaptation of electrodes moving system and the dependence of the artificial external characteristics $I_a(U_a)$ from the characteristics of disturbances based on neural network technology identification and control. With this purpose, we propose to implement adaptive optimization of the dynamics of electrodes moving system based on Neural Network Predictive Controller, which is included into the direct channel of arc lengths (voltages) control subsystem ALCSS and efficient synthesis of optimum arc voltage setting $U^{*}_{a.set}$ is performed by neural network.

When controlling arc steel furnace (ASF) melting modes with prediction of changes of controlled coordinate value – arc lengths (voltage of the arches), the controlled object model - power circuit of arc furnace is used to predict the process of change of the output coordinate. Optimization algorithm is used for operational calculation of a control signal for moving the electrode, which leads to minimization of the deviation between desired and actually received process of changing of the output signal of the model, i.e. the optimization criterion is minimum mean square error of control of arcs lengths. The model of control object – i.e. a model arc furnace power circuit, is implemented using neural network with direct signal distribution, which is characterized by flexibility in modeling objects with the above features and characteristics. Functional diagram of the hierarchical two-contour system with adaptive neural network optimization system of movement dynamics is shown in Figure 4 [7].

At the output of neural regulator control signal $U_c^{U_a *}$ is formed, which by means of an electrode movement mechanism drive EMMD and electrode movement mechanism itself EMM realizes optimal process of moving the electrodes by the criterion of minimum mean square error of deviation between actual and desired processes of changes of arcs lengths (voltages). The neural network of the regulator is adjusted to replicate the model of the arc lengths regulation sub-system "input of electrodes movement drive – output of voltage sensor VS".

The main task of the arc currents control subsystem ACCSS is the realization of high precision replication of power circuit current change process $I_a(t) = F(U_a(t))$, as a partial case of their qualitative stabilization $I_a(t) = I_{a.set}(t) = const$ at a given level, obtained in this subsystem through the use of proportional-integral regulator of arcs currents RSP and high performance of control influence realization.

Thus, due to the realization of optimal dynamics of arcs lengths (voltages) and current control by both local subsystems: ALCSS and ACCSS in proposed two-contour hierarchical neural network system the basic task of melting regimes control is solved: implementation of adaptive optimal control strategies and qualitative dynamic stabilization of electric regime coordinates at the level of synthesized optimal values.

One of the basic strategies of melting regimes control in ASF is the task of maintaining the power of the arcs at the highest possible level under influence of dynamic coordinate and parametric perturbations. In proposed structure (Fig. 4) it is solved at the second level where the prompt synthesis of the optimal arc voltage setting $U^{*}_{a.set}$ by this criteria is performed, which makes it possible to realize the optimal (extreme) power control under the specified time-dependent perturbations.

Effect of the above perturbations results in a change of coordinates of arcs power extremum $P_a(U_a)$. As shown by results of experimental investigations of arc furnaces, most noticeable influence on the coordinates of the arcs power characteristics $P_a(U_a)$ extremum have the dispersion of arc voltages D_{U_a} and change of the supply voltage of three-phase arcs system (change of voltage of arc furnace power leads) U_{sn}.

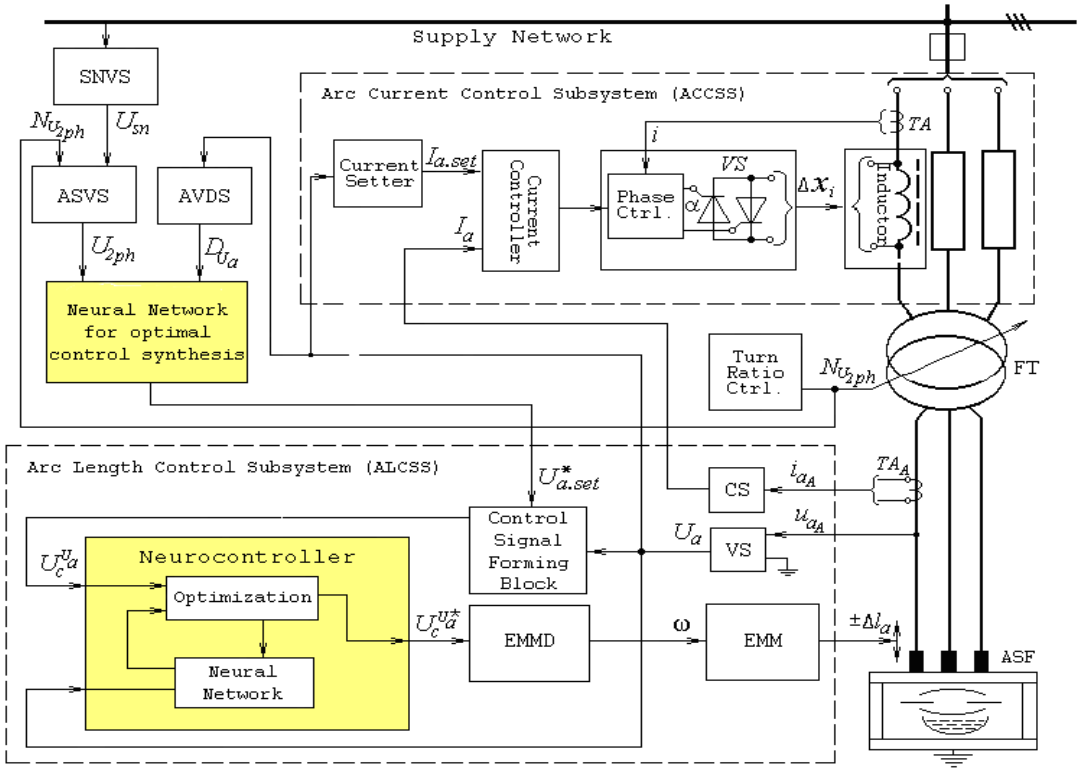

Fig. 4. Hierarchical structure of ASF modes intelligent control system

Identification of a change of abscissa of $P_a(U_a)$ characteristic extremum is performed by neural network (Fig. 4). For this purpose, the current values of arcs supply voltages U_{2ph} and arc voltage dispersions D_{U_a} are applied to its inputs. They are formed on the output of the sensor of arc supply voltage ASVS and arc voltage dispersion sensor AVDS respectively, as a functions of effective (averaged on the period) values of voltages on arcs $U_a(t)$ and averaged on the period voltages $U_{sn}(t)$ on power leads of arc furnace and the number N of current stage of furnace transformer FT applied to the inputs of ASVS and AVDS.

8. Two-contour melting modes control system study

We designed a hierarchic two-level system for the optimum control of the consumption regimes of the arc-furnace reactive power in order to substantially increase the electrical and technical efficiency of heat control and to improve the electromagnetic compatibility of arc-furnace regimes and power-network regimes. As an FRCCS, the lower level uses a high-speed subsystem for optimum reactive furnace power stabilization, which is optimized using criterion (2). In the general case, the upper level employs a static thyristor reactive power compensator. However, our results demonstrate that, for low- and medium-power furnaces, the upper level can contain only a capacitor bank to compensate for the constant component of the reactive power, i.e., to increase the power coefficient to the required level. This increase is necessary to decrease the electrical losses in the furnace power circuit and the energy system. This is possible owing to the fact that the use of the optimum stabilization of the reactive furnace power in the lower level of the subsystem minimizes the fluctuational component of the reactive furnace power to a level at which network voltage oscillations, which are estimated from the flicker dose, do not exceed the normative values.

The efficiency of the designed CS structures and the proposed strategies of the multicriterion control of the electrical regimes of the heat were tested using a digital instantaneous-coordinate model for the power system and the two-circuit control system for arc-furnace electrical-regime coordinates. We studied furnaces of various capacities at various heat stages. To adequately simulate electrical regimes at various stages, we used random arc-length fluctuations, whose statistical characteristics (in particular, a spectral perturbation density function along an arc) corresponded to the real characteristics of these fluctuations at a certain heat stage in an arc furnace.

As an example, Fig. 5 shows the calculated diagrams for the working parameters of a DSP-50 arc furnace and its power network at the stage of well melting for the reactive power consumption regime determined by the designed two-level CS during the operation of an ARDG standard electrohydraulic arc-power controller.

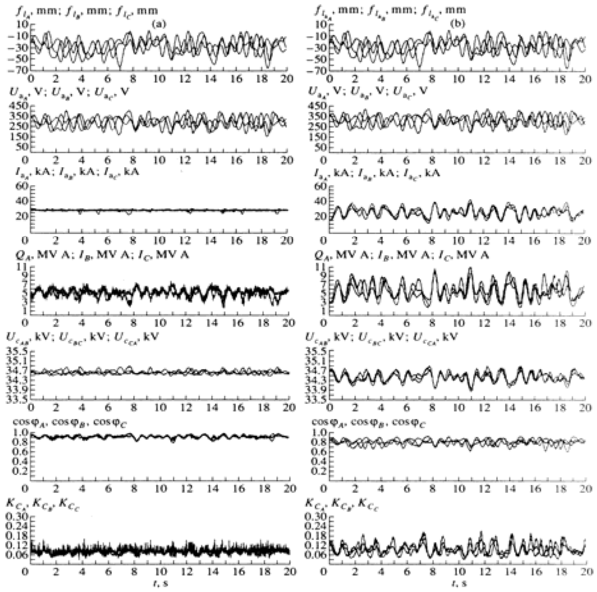

Fig. 5. Diagrams for DSP-50 electrical-regime coordinates at the stage of well melting for the operation of (a) the two-level CS and (b) an ARDG controller

Table 1

Integrated indices for ARDG controller and proposed CS

Index	Two-level CS	ARDG controller
$\overline{U}_a$,V	299.4	313.0
$\overline{I}_a$,kA	29.1	27.3
D_{I_a} , kA^2	0.939	35.4
$\overline{P}_a$,MW	7.05	6.73
$\overline{U}_n$,kV	34.67	34.46
D_{U_n} ,×10^3 V^2	7.27	37.58
$\overline{I}_n$,A	330.2	353.1
$\overline{Q}_c$,MVA	5.26	5.61
D_Q ,*MVA*^{2}	859	3354
$\overline{\cos(\varphi)}$	0.914	0.80
$\overline{K}_{n_{I_n}}$	0.0835	0.0971
δU_n , %	0.947	1.542
F	0.0379	0.220

For each phase, these diagrams show a perturbation variation along the arc length $f_{l_a}(t)$ at this stage of heat, the arc voltage $U_a(t)$, the arc current $I_a(t)$, the furnace reactive power *Q(t)*, the voltage across the power-network busbars $U_n(t)$, the power factor cosφ(*t*), and the current harmonicity perturbation coefficient $K_h(U_a)$. The table 1 gives the integrated indices (mathematical expectations, dispersions) that illustrate the operation efficiency of these systems and are obtained by the statistical processing of the results shown in Fig. 5. In these experiments, the arc voltage was $U_{a.set}$ = 313 V, and an ARDG arc-power controller was used. As a result of the calculations, the nominal arc current is $I_a = I_{a.n}$ = 27.3 kA, and the arc power is $P_a = P_{a.n}$ = 6.73 MW at a secondary voltage of 407 V. For the two-level CS, the secondary transformer voltage was increased by 10%, and the artificial external furnace characteristic was synthesized by functional (2) under conditions of a network voltage dispersion minimum. This minimum corresponds to the following optimum values: γ*=0.75 and $U_{a.set}$ = 299 V.

The calculated integrated indices demonstrate that all of the indices are significantly improved when the two-level CS is used instead of an ARDG-type arc-power controller. For example, the arc-current dispersion decreases by 30-40 times, and the flicker dose F decreases by a factor of five to six. The loading current harmonic distortions coefficient decreases by 14-15%; the power factor increases by 14-15%; the arc power increases by 4-5%; and the deviation of the voltage across furnace busbars from the nominal voltage decreases by 1.4-1.6%.

9. Conclusions

The use of a high-speed subsystem that controls the resistance of a reactor involved in the power circuit of the primary winding of a furnace transformer in the structure of a proposed two-circuit CS allows one to realize the multicriterion optimum control of an EAF electrical regime. This control provides a substantial increase in the electrical and technical efficiency of arc-furnace regimes and improves the indices of the electromagnetic compatibility of the furnace and its power system.

The proposed two-circuit CS can be used to run heats at the minimum number of switchings of a furnace transformer, which decreases the heat time and increases the reliability of the furnace power supply. Variable setting actions for the realization of the multi-criterion optimum control in this case, i.e., at U_{2p}=const, are only represented by a preset arc voltage $U_{a.set}$ and an $I_a(U_a)$ AEC relation for an arc furnace.

The substantial induced decrease in the amplitude and dispersion of the arc-current and furnace reactive power oscillations decreases the flicker dose by a factor of five to six and decreases the electrodynamic forces in the elements of the electric power facilities and their mechanical vibrations. As a result, the reliability of this equipment increases.

Efficiency of optimal control strategies implementation increased due to their synchronization with changes of melting stages, which are identified by hierarchical neural-network based control system.

Solutions for optimum stabilization of electrical mode coordinates were proposed. Conducted studies and obtained results proved efficiency of complex solutions of multicriterion control and optimum stabilization tasks.

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СИСТЕМА БАГАТОКРИТЕРІАЛЬНОГО ІНТЕЛЕКТУАЛЬНОГО КЕРУВАННЯ РЕЖИМАМИ ПЛАВЛЕННЯ ТА ОПТИМАЛЬНОЇ СТАБІЛІЗАЦІЇ КООРДИНАТ ЕЛЕКТРИЧНОГО РЕЖИМУ ДУГОВОЇ СТАЛЕПЛАВИЛЬНОЇ ПЕЧІ

Лозинський О.Ю., .,Паранчук Р.Я., Паранчук Я.С

Анотація: Запропоновано ієрархічну структуру системи адаптивного багатокритеріального оптимального керування режимами плавлення в трифазній дуговій сталеплавильній печі. Розроблено моделі синтезу багато-критеріального оптимального керування оптимального режимами. Адаптація оптимального керування та якісної стабілізації координат електричного режиму у розробленій структурі виконується у функції зміни технологічних стадій та з врахування поточних технологічних стадій, які визначаються нейронною мережею.

Orest Lozynskyi – Director of the Institute of Energetics and Control Systems at Lviv Polytechnic National University, doctor of science professor. In 1965 he graduated from the electromechanical department of Lviv Polytechnic Institutemajoring in electric drives and automation of industrial installations and technological complexes. In 1974 he defended his candidate of science thesis on "System of optimal control of electric arc furnace electrodes movement", and in 1996 – his doctor of science dissertation "Control system of arc steel furnace mode based on probability models of processes". Orest Lozynskyi started his career at the department of electric drives and automation of industrial installations in 1965 as an engineer. Then in 1982 he was appointed an associate professor and in 1997 – a professor. While working at the university prof. Lozynskyi holds the posts of Dean of Electromechanical Faculty (1989), Head of the Department (1992), Director of the Institute of Energetics and Control Systems (2001). In 2005 he became an honoured scientist of Ukraine. He is the author of over 330 scientific and methodological works, as well as 3 monographs.

Yaroslav Paranchuk – Professor of the Department of Electric drives and automation of industrial installations at Lviv Polytechnic National University, doctor of science In 1974 he graduated from the Electromechanical Faculty of Lviv Polytechnic Institute majoring in Electric Drives and automation of industrial installations and technological complexes. In 1991 he defended his candidate dissertation on "Rapid positioning control system of arc steel melting furnace electrical mode" and in 2006 – doctor of science thesis on "Multi-criterion optimization of the complex "arc" steelmaking furnace – electric supply network". His research work is aimed at the solution of scientific issues, and applied tasks in the field of automation and optimization of arc steel furnaces, energy and electromagnetic compatibility modes of powerful electro-dynamic objects with stochastic load mode. He is the author and co-author of 2 monographs, over 130 scientific articles, 7 textbooks. Prof. Paranchuk has been granted more than 30 patents of Ukraine and the Russian Federation.

Roman Paranchuk – a research associate, engaging in software developer, candidate of science. He graduated from the Faculty of Physics of Lviv I. Franko National University in 2000 majoring Radio Physics and Electronics.A year later he became a graduate of Lviv Polytechnic University and was qualified in Electric drives and automation of industrial installations and technological complexes. In 2004 he defended his candidate dissertation on "Research into conditions of convergence for nonlinear electric circuits". His research activity is related to the control automation, and modelling of complex nonlinear systems.

He is the author and co-author of one monograph, more than 40 scientific papers, 3 textbooks. He has been granted 5 patents of Ukraine and the Russian Federation.