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THEORETICAL BASIS OF ENERGY EFFICIENCY CRITERION-BASED OPTIMAL CONTROL OF ARC STEEL_MELTING FURNACE MODES TAKING INTO ACCOUNT 3-DIMENSIONAL PHASE CURRENT DISTRIBUTION

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Abstract: The purpose of the article is to develop a method for synthesis of the operative adaptive optimal control of the electric mode (EM) of an arc steel-melting furnace (ASF) by energy efficiency criteria based on three-dimensional (3-D) distribution of arc currents. The basis of the created method is the use of operative information on the parameters of 3-D distribution of arc currents and the search for the appropriate optimal control – set points for arc currents of a double-loop system of controlling the electric mode of an arc steel-melting furnace. There have been obtained partial optimality criteria to minimize the specific energy consumption, the steel price per ton, and to maximize the hourly productivity of an arc furnace, as well as an algorithm for operational synthesis and implementation of the optimal control vector according to the chosen criterion, taking into account the model of 3-D current distribution. For the first time, based on the operative on-line control of 3-D arc currents distribution, partial criteria have been obtained for the synthesis of adaptive optimal control of the electric mode of an arc furnace, which makes it possible to comprehensively improve the energy efficiency and electromagnetic compatibility of the arc furnace modes and the electric supply network. The implementation of the created method of adaptive optimal control and the algorithm for its implementation in the structure of a double-loop control system of electric melting mode will allow us, in comparison with the known single-loop control structures, to improve the indices of electrotechnological efficiency and electromagnetic compatibility, and to obtain higher dynamic accuracy of stabilization the electric mode coordinates at the level of the operatively synthesized optimal arc current set points.

Key words: arc steel-melting furnace, electric mode, three-dimensional phase current distribution, stochastic control, optimization, adaptation, energy efficiency

1. Introduction

Today in Ukraine, arc steel-melting furnaces are the main technological units for the production of high-alloy steels and precision alloys. This is consistent with the global trend of increasing the proportion of steels smelted in arc furnaces and correspondingly decreasing their output in converters. The indicated state and tendency of development of steel-melting units as a priority set the task of improving the existing electric steel-melting units – arc steel-melting furnaces in the direction of complex improvement of the indicators of electrotechnological efficiency. Such indicators include specific electricity costs, the price per ton of recycled steel, furnace performance, etc.

Characteristic features of arc steel-melting furnaces as an object of control are their nonlinearity, phase asymmetry of load modes, non-stationarity of random processes of change in parametric and coordinate perturbations in the power supply circuit of the three-phase arc system, etc. These features are a significant obstacle to the implementation of steel-melting modes with high rates of electrotechnological efficiency.

One of the most effective approaches to comprehensive improvement of the performance of electric arc furnaces is to create new and improve existing solutions for electrical control systems in order to realize the strategies of adaptive optimal (single or multi-criteria) energy efficiency control. Another approach, equally effective among existing ones, is the development of circuit and system solutions for comprehensive improvement of the quality of dynamic stabilization of electrical coordinates – voltages, currents and power of arcs at a given level. High-quality implementation of this approach will further enhance the effectiveness of the former [1].

The use of solutions to implement the above approaches will reduce the specific energy consumption, improve the performance of electric arc furnaces, reduce the power losses in the power circuit and power system of an arc steel-melting furnace and, as a result, increase the competitiveness of electric steels and precision alloys on both the domestic and foreign markets of metal products [2].

The purpose of this work is to develop a method for the operative synthesis of adaptive optimal control of the electric mode of an arc furnace according to the criteria of energy efficiency, which takes into account the random phase-related nature of the processes of change in electric melting coordinates, which is described by the density distribution of the three-dimensional vector of arc currents. This control model, which corresponds to the stochastic nature of the processes in the power supply circuit of three-phase arcs and in the arc intervals themselves, will allow us, in comparison with the existing control models, to comprehensively improve the indicators of electrotechnological efficiency of melting processes in arc steel-melting furnaces.

The novelty of the developed approach is to use in the model of operative synthesis control effects of the current dependence of the density distribution of a three-dimensional vector of arc currents. This approach will adequately take into account the real phase correlation of the processes of phase current change, which reflects on the processes of change in integral estimates of of electrotechnological efficiency indicators – specific energy costs, useful active power, and, consequently, the performance of the arc furnace.

The theoretical foundations of the proposed model of adaptive optimal control, i.e operative in the on-line mode synthesis of the vector of phase settings of currents of arcs of the arc steel-melting furnace power regulator are as follows.

It is well known that the optimization of the electric mode of the arc furnace is based on technical and economic indicators, such as the time of metal melting $T_m = \dfrac{\Delta W_m}{\overline{P}_{up}}$ the specific energy consumption $W_{sc} = \dfrac{\Delta W_m}{G_{ch}} \cdot \dfrac{\overline{P}_a}{\overline{P}_{up}}$ and the cost of melting a ton of steel

$$C = H + DT_p + EW_{sc},$$

where *H, D, E* are the stable coefficients determined for a certain furnace according to the results of its operation; ΔW_{us} represents the energy required to melt the loaded charge (scrap metal); G_{ch} stands for the weight of the charge; $\overline{P}_a$ denotes the average value of the active power consumed by the electric furnace during the melting of the charge; $\overline{P}_{up}$ is the average value of the useful arcs power transmitted to the metal during the melting of the charge.

For the deterministic nature of the description of the processes in an arc furnace, active and useful power, subject to sinusoidal instantaneous currents and voltages of arcs, are determined by the following known expressions:

$$P_a = \sum_{i=A,B,C} \left[P_{ai}\left(I_{ai}\right) + I_{ai}^2 r_i \right],$$

$$P_{up} = \sum_{i=A,B,C} P_{ai}\left(I_{ai}\right) - P_{hl},$$

where P_{ai} is the active power of the arc of the i-th phase provided that the current of the arc I_{ai} (the power of the arcs is only active); r_i stands for the resistance of the short-network circuit of the i-th phase; P_{hl} represents the power of heat losses in the furnace space; $i=A,B,C$ denotes the phase indices.

Under real conditions, the arc currents fluctuate continuously with respect to their mean (set) values (arc settings), and these fluctuations are random in nature.

It is clear that taking into account the random nature of the processes in an ASF to obtain the average values $\overline{P}_{hl}$ and $\overline{P}_{up}$ requires knowledge of the laws of distribution of electrical coordinates of the process of electric melting. The most generalized coordinate in arc furnaces is the currents of arcs of individual phases. It should also be noted that the accepted by many authors model of finding the average values of these powers [3-5], as the sum of their equal average values for the phases of the arc furnace, i.e.

$$\overline{P}_a = \frac{3}{\sqrt{2\pi D}} \cdot \int_0^{I_s} I_a \cdot \sqrt{U_{ph}^2 - \left(I_a x\right)^2} \cdot e^{-\frac{\left(t_a - r_a\right)^2}{2D}} dI_a,$$

$$\overline{P}_{up} = \frac{3}{\sqrt{2\pi D}} \cdot \int_0^{I_s} \left(\sqrt{U_{ph}^2 - \left(I_a x\right)^2} - I_a r \right) I_a \cdot e^{-\frac{\left(t_a - r_a\right)^2}{2D}} dI_a,$$

where U_{ph} is the phase supply voltage of the arc furnace; *x* is the reactance of a short-network phase; $\overline{I}_a$ is the average (given) value of an arc current *D* is the dispersion of an arc current, does not give a correct evaluation of their values, since the level of this indicator is due to the one-dimensional law of current distribution in a particular phase when neglecting the phase interconnection and asymmetry of the short- network circuit and the asymmetric nature of the parametric and coordinate perturbations in all phases of the arc furnace.

The values of $\overline{P}_a$ and $\overline{P}_{up}$ found in this model do not correspond to the actual melting conditions in the arc furnace because this model does not take into account the correlation relationship between the phase currents. It is clear that the design of current-carrying elements in an ASF can be constructed with symmetric current leads, but the perturbations and phase interconnections of the parameters acting in separate phases of the ASF cannot be assumed symmetrical. Therefore, the condition of uncorrelated phase currents can only be accepted for the first approximation. Hence, finding the aforementioned values of average power must be based on the following provisions:

- it is necessary to form three-dimensional functions of P_a and P_{uh}, the main arguments of which will be the arc current values;
- finding the mean values of $\overline{P}_a$ and $\overline{P}_{up}$ should be based on the density distribution of the three-dimensional vector of arc currents of individual phases.
- It should be noted here that the phase correlation of phase currents is due to [6]:
- primary perturbations of arc voltages of separate phases due to random changes of $a_i(t)$, $\beta_i(t)$, $L_{ai}(t)$, i.e. due to the components that are included in the expression for the arc voltage of the *i*-th phase:

$$U_{ai}(t) = a_i(t) + \beta_i(t) L_{ai}(t),$$

where $a_i(t)$ – represents the anode-cathode decrease in arc voltage of the *i*-th phase; $\beta_i(t)$ – stands for the arc gradient of the i-th phase; – denotes the arc length of the i-th phase. – the connection between the currents of individual phase conductors due to $M\frac{dt_i}{dt}$, and the randomness of the value of the induction coefficient *M*;

– random overflows of phase currents when using a three-wire arc supply system.

The electric equivalent circuit of a short network of one phase of an arc furnace, subject to the non-sinusoidality [7] of the arcs currents and voltages, is shown in Fig. 1.

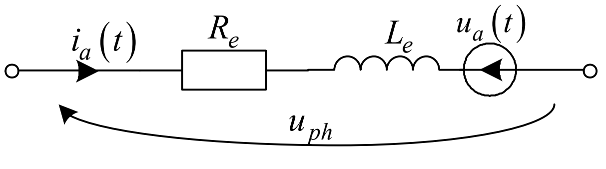

Fig. 1. Electric equivalent circuit of one phase of an AF short network.

In this Figure, R_e and L_e denote the equivalent resistance and inductance of a single phase of the conductor taking into account interphase mutual inductances; $u_a(t)$, $i_a(t)$ stand for the instantaneous values of non-sinusoidal voltage and current of the arc; u_{ph} represents the instantaneous value of the sinusoidal phase voltage of the corresponding phase of the furnace transformer.

From Fig. 1 it follows that:

$$u_{ph} = i_a(t) R_e + L_e \frac{di_a(t)}{dt} + u_a(t),$$

From which

$$u_a(t) = u_{ph} - i_a(t) R_e - L_e \frac{di_a(t)}{dt}, \tag{1}$$

Then the instantaneous arc power is written as

$$p_a(t) = u_a(t) i_a(t)$$

and the active arc power of one phase will be calculated by the following expression (2)

$$P_a = \frac{1}{T}\int_0^T p_a(t)\,dt = \frac{1}{T}\int_0^T u_a(t) i_a(t)\,dt. \tag{2}$$

Substituting $u_a(t)$ from expression (1) into expression (2), we obtain

$$P_a = \frac{1}{T}\int_0^T \left[u_{ph} - i_a(t) R_e - L_e \frac{di_a(t)}{dt} \right] i_a(t)\,dt =$$
$$= \frac{1}{T}\int_0^T u_{ph} i_a(t)\,dt - \frac{1}{T}\int_0^T i_a^2(t) R_e\,dt - \frac{1}{T}\int_0^T L_e i_a(t)\,di_a(t).$$

Replace $i_a(t)$ and $u_a(t)$ with equivalent sinusoidal values based on the equality of the respective root-mean-square (RMS) current and voltage of the arc. Then, expression (1) based on the symbolic method is transformed into the following form:

$$\begin{aligned} \dot{U}_a &= \dot{U}_{ph} - \dot{I}_a R_e - j\omega L_e \dot{I}_a = \\ &= \dot{U}_{ph} - \dot{I}_a (R_e + j\omega L_e). \end{aligned} \tag{4}$$

This expression will correspond to the vector diagram shown in Fig. 2.

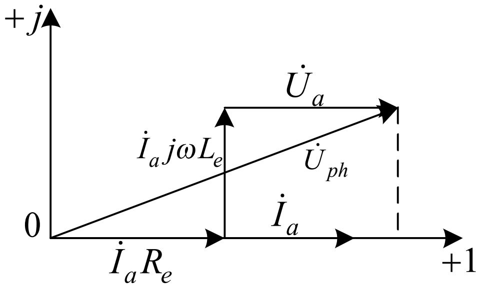

Fig.2. Vector voltage diagram of one phase of a short arc furnace network circuit.

Based on the above vector diagram, we can write that

$$u_a = \sqrt{U_{ph}^2 - \left(I_a \omega L_e\right)^2} - I_a R_e .$$

And then the arc power is calculated as

$$P_a = U_a I_a ,$$

where $U_a I_a$ – are the RMS voltage and current of the one-phase arc.

Let us represent a mathematical expectation of the three-phase useful power as a triple integral of the product of the function P_{up} and the density of the three-dimensional vector of the currents I_{ai}:

$$\begin{aligned}
&P_{up}\left(\bar{I}_{aA}, \bar{I}_{aB}, \bar{I}_{aC}\right) = \\
&= \int_0^{I_{sA}} \int_0^{I_{sB}} \int_0^{I_{sC}} \left\{ \left[\sqrt{U_{phA}^2 - \left(I_{aA} x_A\right)^2} - I_{aA} r_A \right] I_{aA} + \right. \\
&+ \left[\sqrt{U_{phB}^2 - \left(I_{aB} x_B\right)^2} - I_{aB} r_B \right] I_{aB} + \\
&+ \left[\sqrt{U_{phC}^2 - \left(I_{aC} x_C\right)^2} - I_{aC} r_C \right] \cdot \\
&\left. \cdot I_{aC} \right\} f\left(I_{aA}, I_{aB}, I_{aC}\right) dI_{aA} dI_{aB} dI_{aC} ,
\end{aligned}$$

where I_{si} is the operative short-network circuit current of the i-th phase.

Similarly, the expression for the mathematical expectation of the active power of the three phases of a three-phase power supply system of ASF arcs without a zero conductor, provided that the arc is an active element, is written as:

$$\begin{aligned}
&\bar{P}_a\left(\bar{I}_{aA}, \bar{I}_{aB}, \bar{I}_{aC}\right) = \int_0^{I_{sA}} \int_0^{I_{sB}} \int_0^{I_{sC}} \left\{ I_{aA} \sqrt{U_{phA}^2 - \left(I_{aA} x_A\right)^2} + \right. \\
&\left. + I_{aB} \sqrt{U_{phB}^2 - \left(I_{aB} x_A\right)^2} + I_{aC} \sqrt{U_{phC}^2 - \left(I_{aA} x_C\right)^2} \right\} \times \\
&\times f\left(I_{aA}, I_{aB}, I_{aC}\right) dI_{aA} dI_{aB} dI_{aC} .
\end{aligned}$$

In the last two expressions, $f\left(I_{aA}, I_{aB}, I_{aC}\right)$ is the distribution density of the three-dimensional vector of arc currents which is found in [8, 9] in the form

$$\begin{aligned}
&f\left(I_{aA}, I_{aB}, I_{aC}\right) = \frac{1}{\left(2\pi\right)^{\frac{3}{2}} \sqrt{\det \Lambda_I}} \\
&\exp\left\{ -\frac{1}{2} \frac{1}{\det \Lambda_I} \left[A_{AA}\left(I_{aA} - \bar{I}_{aA}\right)^2 + \right.\right.
\end{aligned}$$

$$\begin{aligned}
&+ A_{BB}\left(I_{aB} - \bar{I}_{aB}\right)^2 + A_{CC}\left(I_{aC} - \bar{I}_{aC}\right)^2 + \\
&+ 2A_{AB}\left(I_{aA} - \bar{I}_{aA}\right)\left(I_{aB} - \bar{I}_{aB}\right) + \\
&+ 2A_{AC}\left(I_{aA} - \bar{I}_{aA}\right)\left(I_{aC} - \bar{I}_{aC}\right) + \\
&\left.\left. + 2A_{BC}\left(I_{aB} - \bar{I}_{aB}\right)\left(I_{aC} - \bar{I}_{aC}\right) \right] \right\} .
\end{aligned}$$

Found in expression (3) the average value of the useful power of the arc should be adjusted by the amount of heat losses, which for a particular arc furnace with sufficient accuracy can be assumed constant. This indicator does not depend on the phase currents, but is only determined by the design, the state of the arc furnace lining and the total energy input into the furnace space.

Thus, the calculation of the average values of $\bar{P}_a$ and $\bar{P}_{up}$ according to expressions (3) and (4) is adequate to the actual conditions of electric melting in the arc furnace model of their calculation and therefore the value of energy indicators both for the problems of mode optimization by technical and economic criteria, and for the problems of mode stabilization at the level of guideline values should be calculated using this model.

Therefore, we are able to find an equivalent average value of the useful power of the three phases, that is, the total power given to the metal by three arcs. In this case, it becomes possible to form a set of technical and economic criteria $T_m = T_{m,min}$; $C = C_{min}$; $W_{sc} = T_{sc,min}$ for unconstrained extremum problems and similar criteria

$$\begin{aligned}
&C = C_{min} \text{ at } W_{sc} = W_{sc,min.p} \\
&T_m = T_{m,set} \text{at} W_{sc} = W_{sc,min.p} \\
&W_{sc} = W_{sc,set} \text{ at } T_m = T_{m,min.p} \\
&C = C_{set} \text{ at } T_m = T_{m,min.p} \\
&C = C_{set} \text{ at } W_{sc} = W_{sc,min.p} \\
&P_{up} = P_{up,set} \text{ at } W_{sc} = W_{sc,min.p}
\end{aligned} \qquad (5)$$

for constrained extremum problems.

It is clear that for cases of absolute extremum, the equation for finding the required optimal arc currents set points for the ASF phases will be written as:

$$\frac{dW_{sc}}{d\bar{I}_a} \Rightarrow 0 \text{, where } i = A,B,C.$$

Given the above expression for W_{sc.}, we write

$$\begin{aligned}
&\frac{dW_{sc}}{d\bar{I}_{ai}} = \frac{d}{d\bar{I}_{ai}} \left(\frac{\Delta W_{sc}}{G_{ch}} \cdot \frac{\bar{P}_a}{\bar{P}_{up}} \right) = \\
&= \frac{\Delta W_{sc}}{G_{ch}} \cdot \frac{\bar{P}_{up} \dfrac{d\bar{P}_a}{d\bar{I}_{ai}} - \bar{P}_a \dfrac{d\bar{P}_{up}}{d\bar{I}_{ai}}}{\bar{P}_{up}^2} \Rightarrow 0,
\end{aligned}$$

from which we obtain an equation for finding the optimal settings in the form:

$$\overline{P}_{up}\frac{d\overline{P}_a}{d\overline{I}_{ai}}-\overline{P}_a\frac{d\overline{P}_{up}}{d\overline{I}_{ai}}\Rightarrow 0\,.$$

It should be noted here that, as mentioned above, the values of $\overline{P}_{up}$ and $\overline{P}_a$ are calculated from expressions (3) and (4) obtained above, which take into account the real phase interconnection and asymmetry of changes in the electric mode coordinates during melting.

As for the cases of finding the optimal set points for any of the above multi-criteria optimization problems, here, as an example, the equation for the constrained extremum of the generalized objective functional can be represented as follows:

$$\lambda_W\frac{dW_{sc}}{d\overline{I}_a}+\lambda_C\frac{dC}{d\overline{I}_a}\Rightarrow 0\,, \qquad (6)$$

which includes the weight coefficients of the partial criteria λ_W, λ_C, which are obtained by known expert methods.

Let us dwell in more detail on another criterion for the optimization of the electric mode of an ASF, namely, the criterion of providing a minimum useful specific (steel price per ton) electricity consumption under the melting of the charge in a given time T_p.

Note that the predetermined melting time is based on the following considerations. The total time from the start of melting to the moment the melt is drained into the ladle consists precisely of the time of melting and the time of the technological stages that turn the liquid consistency of metal into steel of the desired grade. If the second component of this time can be considered constant, then the specified melting time will be based on the condition that the mentioned total time cannot be less than the time of logistic operations for ASFs servicing. Mathematically, this criterion can be expressed as

$$W_{sc}=\frac{1}{G_{ch}}\int_0^{T_p}\overline{P}_{up}\left(t\right)dt\rightarrow\min\,.$$

Performing the procedure for minimizing the partial criterion

$$\begin{aligned}&W_{sc}\left(\overline{I}_{aA},\overline{I}_{aB},\overline{I}_{aC}\right)=\\&=\frac{1}{G_{ch}}\int_0^{T_s}\overline{P}_{us}\left(\overline{I}_{aA},\overline{I}_{aB},\overline{I}_{aC},t\right)dt\end{aligned} \qquad (7)$$

by solving the following system of equations:

$$\begin{aligned}&\frac{\partial W_{sc}\left(\overline{I}_{aA},\overline{I}_{aB},\overline{I}_{aC}\right)}{\partial\overline{I}_{aA}}=0;\\&\frac{\partial W_{sc}\left(\overline{I}_{aA},\overline{I}_{aB},\overline{I}_{aC}\right)}{\partial\overline{I}_{aB}}=0;\\&\frac{\partial W_{sc}\left(\overline{I}_{aA},\overline{I}_{aB},\overline{I}_{aC}\right)}{\partial\overline{I}_{aC}}=0.\end{aligned} \qquad (8)$$

allows us to obtain the components of the control vector – settings for currents of arcs of individual phases of the arcs power regulator, which minimize the specific energy consumption at the *i*-th interval of stationarity of the processes of change in of the electric mode coordinates of the *j*-th technological stage of electric melting.

The stationarity interval, as shown by the performed experimental studies on arc furnaces of different capacity, is $T_s\cong 100-180$ s [10, 11]. The vector of control effects $\left(\overline{I}_{aA},\overline{I}_{aB},\overline{I}_{aC}\right)$ obtained by minimizing (8) according to the results of process monitoring at the i-th stationarity interval is set to control the next *i+1* interval.

Given that the parameters of the stochastic characteristics of parametric and coordinate perturbations arising in the power circuit of a three-phase arc system at adjacent stationarity intervals vary slightly, and the quality (dynamic accuracy) of stabilization of the arc currents at the level of the specified set points $\left(\overline{I}_{aA},\overline{I}_{aB},\overline{I}_{aC}\right)$ is high, especially when using a double-loop system for controlling the arc currents [11], then the correction of the control vector for the set points of the phase currents will lead to the displacement working point of criterion (7) in the space of changing the set points in the direction of reducing their assessments. The control vector $\overline{I}_{aj}\left(j=A,B,C\right)$ of the power controller of the arcs is synthesized for the next and +2 nd stationarity interval according to the selected energy efficiency criterion similarly according to the results of the monitoring the process $\overline{I}_{aj}\left(t\right)$ at the *i*+1-st interval, and so on.

The algorithm for the implementation of the developed methodology for the operative synthesis and implementation of the vector $\left(\overline{I}_{aA},\overline{I}_{aB},\overline{I}_{aC}\right)$ of optimal control of a double-loop ACS of the electric mode of an arc steel-melting furnace according to the criterion of minimum useful specific energy consumption is shown in Fig. 3.

By the same algorithm, optimal controls are synthesized and implemented for other partial optimality criteria (5) or for multi-criteria control (6), models of which are implemented in block 4 of the above algorithm. The difference is in the model of block 4, which must fit the model of another criterion.

Therefore, the above synthesis algorithm for the optimal control of the electric mode of the melting process can be used for other criteria, for example, for the generalized criterion for maximum furnace performance, or for the additive optimality criterion (6),

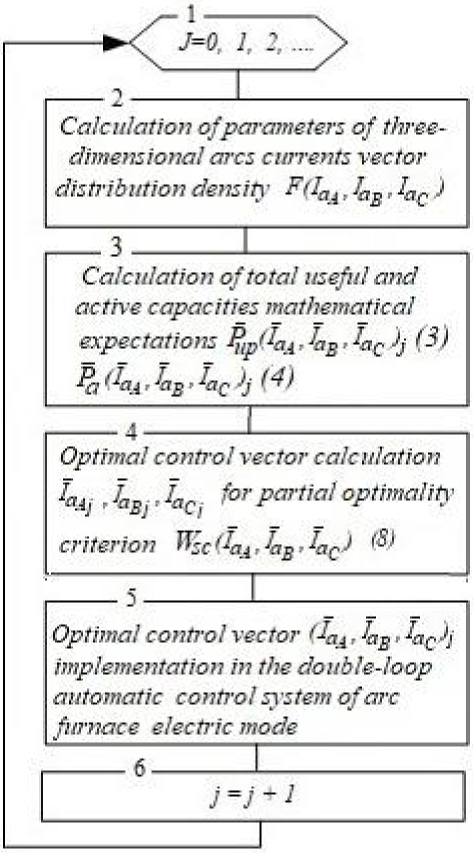

Fig. 3. Block-diagram of the algorithm for operative synthesis of optimal control vector of a double-loop ACS of ASF EM.

formed on the basis of the partial criteria mentioned above. The main elements that form these criteria are the average useful and active powers, and the values of these powers $\bar{P}_{hl}$ and $\bar{P}_{up}$ are determined by the calculation method proposed in the article, which takes into account the three-dimensional law of phase current distribution. This makes it possible to implement a strategy of adaptive optimal control over the entire energy-intensive process of melting the solid charge under the conditions of continuous action of intense coordinate and parametric perturbations, the statistical characteristics of which change during melting and with sufficient accuracy are accepted constants at each interval.

Thus, the process of optimizing the ASF electric mode should be carried out on the basis of the above mentioned energy-efficient partial criteria or according to the generated generalized functionals with obligatory consideration of the correlation of the ASF phase currents, i.e. the optimization of the melting process should be carried out on the basis of generalized energy that is transferred to the heating of the charge.

Conclusion

1. It is the first time that generalized expressions are obtained for the average value of the active and useful power of the three phases of a three-phase power supply system of AC ASF arcs without a zero conductor taking into account phase correlation of arc currents.

2. An ingenious technique for the operative synthesis of the vector of adaptive optimal control of the ASF electric mode has been developed based on the use of a three-dimensional vector of arc currents that allow the stochastic phase-interrelated nature of the arc current fluctuations to be taken into account throughout the melting process.

3. The proposed algorithm for implementing the developed model of the operative synthesis of the vector of optimal arc current set points allows tracking the drift of the extremum of the formed scalar or vector optimality criterion in the space of change in control effects of the double-loop structure of the ACS of the ASF electric mode.

4. Using the adaptive optimal control synthesis model developed in the article and the algorithm for its implementation, it is possible to comprehensively improve a number of indicators of electrotechnological efficiency by moving the operating point of the furnace to the extremum of the selected criterion of optimality from the position where the operating point of the furnace enters under the influence of non-stationary and phase-asymmetric parametric and coordinate perturbations.

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ТЕОРЕТИЧНІ ЗАСАДИ ОПТИМАЛЬНОГО КЕРУВАННЯ РЕЖИМАМИ ДУГОВОЇ ПЕЧІ НА ОСНОВІ КРИТЕРІЇВ ЕНЕРГОЕФЕКТИВНОСТІ З ВРАХУВАННЯМ ТРИВИМІРНОГО РОЗПОДІЛУ СТРУМІВ ФАЗ

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Мета статті – створити метод синтезу оперативного адаптивного оптимального керування електричним режимом дугової сталеплавильної печі за критеріями енергоефективності на основі тривимірного розподілу струмів дуг. В основу створеного методу покладено використання оперативної інформації про параметри тривимірного розподілу струмів дуг та пошук відповідного оптимального керування – уставок за струмами дуг двоконтурної системи керування електричним режимом дугової сталеплавильної печі. Отримано часткові критерії оптимальності для мінімізації питомих витрат електроенергії, ціни тонни виплавленої сталі та максимізації погодинної продуктивності дугової печі, а також розроблено алгоритм оперативного синтезу та реалізації вектору оптимального керування за вибраним критерієм з врахуванням моделі тривимірного розподілу струмів фаз. Вперше на основі оперативного контролю тривимірного розподілу струмів дуг отримано часткові критерії для синтезу адаптивного оптимального керування електричним режимом дугової сталеплавильної печі, що дало змогу комплексно покращити показники енергоефективності та електромагнітної сумісності режимів дугової печі та електромережі. Реалізація створеного методу адаптивного оптимального керування та алгоритму для його реалізації в структурі двоконтурної системи керування електричним режимом плавлення дасть змогу порівняно із відомими одноконтурними структурами керування поліпшити показники електротехнологічної ефективності та електромагнітної сумісності ы отримати вищу динамічну точність стабілізації координат електричного режиму на рівні оперативно синтезованих оптимальних уставок за струмами дуг.

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