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REPRESENTATION OF ELECTRICAL MODE IN ARC FURNACES BY A STATE CHANGE MODEL AND DETERMINATION OF THE POSSIBILITIES OF THESE STATES

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Abstract: It is the first paper where the electrical mode of an arc furnace (AF) is proposed to be considered as a state change. This work also proposes a methodology for calculating the time values of the probabilities of these states. The methodology is based on the representation of state-change processes by the Markov model of continuous time, discrete state (CDS) stochastic processes.

The state of electrical mode in each phase of an arc furnace is identified by the value of arc current that can be set for a given melting period, may be in the range of permitted deviations, or may get to the range of large operational or emergency deviations. Assuming that the system goes from state to state under the action of the Poisson flows of events, the concept of intensity of disturbance flows, and the intensity of flows of control actions are introduced. This makes it possible to form a system of Kolmogorov differential equations to change the state probabilities of the AF electrical mode. The solution of the system results in obtaining time dependencies of change in state probabilities.

When analyzing graphs of changes over time in the probabilities of AF electrical mode states, it is possible to choose the desired intensity of the flow of control actions, which ensures that the electrical mode is in a given state under the action of the corresponding disturbance flow.

Key words: arc furnace, electrical mode, probability of the electrical mode state, Markov stochastic processes, intensity of disturbance flows, intensity of control actions.

1. Introduction

Electric arc furnaces are powerful electro-technological installations that belong to a class of sophisticated systems and are characterized by the random nature of load and parametric disturbances in arc spaces and power supply circuits of three-phase arcs. The specified load characteristics complicate the process of controlling such objects and impose appropriate limitations on systems engineering – models, methods for and approaches to improving the existing systems of mode control and regulation of electric coordinates.

The problem of integrated improvement of energy efficiency and electromagnetic compatibility of arc furnaces is resulted from the need to increase the competitiveness of arc-furnace steel and high alloys on the domestic and foreign markets of metal products. The arc furnace mode state is largely determined by the level of perfection of the control system that, in turn, is determined by the accepted model of its synthesis. It is clear that for such electro-technological stochastic objects, it is most appropriate to use models based on the probabilistic characteristics of disturbance processes, that is, those that are most fully consistent with the processes occurring in arc furnaces.

In a series of works, the control actions in arc furnaces are synthesized by the use of probabilistic models of processes [1–5]. However, the authors of these works use moment functions of different coordinates as a criterion for the functioning of the system, and synthesize the process of control actions based on the spectral characteristics of such coordinates.

The issue of controlling the electrical mode of arc furnaces by ensuring that the latter is in a given state, as far as we know, is most likely not to have been studied by any of the researchers. Therefore, the purpose of this work is, first of all, the determination of time characteristics of the AF electrical mode state probabilities, followed by the use of these dependencies for the synthesis of intensities of control action flows that provide the greatest probability of the existence of a given state.

The most appropriate approach to solving the first problem is to create a model for changing the electrical mode states in arc furnaces, based on the theory of Markov processes.

2. Research results

For the most general case, we present a dynamic system for controlling the electrical mode in an arc furnace by the state-change model (Fig. 1).

In this Fig. 1, the following notations are used:

- state $X1$– characterizes a given electrical mode of an arc furnace;

- state $X2$ – is characterized by permitted deviations of the electrical mode from a given value;
- state $X3$– is characterized by large operational or emergency deviations of the electrical mode.

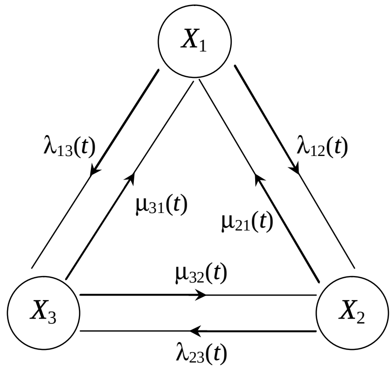

Fig. 1. A graph of the electrical mode states in an arc furnace, where $m_{3,1}(t)$, $m_{3,2}(t)$, $m_{2,1}(t)$, $l_{1,3}(t)$, $l_{1,2}(t)$, $l_{2,3}(t)$ are the intensities of control system response and the intensities of disturbances of the electrical mode, respectively.

The change in the states i, j of such a system is the effect of the action of one or another flow of events with the intensity, for example $l_{ij}(t)$, at the time moments when the first event of the flow occurs.

The mathematical expectation of the number of flow events that occurring during the elementary time interval Δt equals $l_{ij}(t)\cdot\Delta t$. Accurate to higher-order infinitesimals, this variable can be identified as a probability of occuring a single event during an elementary time interval, since the probability of occuring more than one event during $(t+\Delta t)$ is neglected.

Thus, each state of the arc furnace electrical mode can vary under the action of two flows of actions – the flow of disturbances that act in an arc furnace and take the electrical mode out the given state, and a flow of control actions, which are the control system response to eliminate the electrical mode deviations from the given values. Then, the probability $P_j(t+\Delta t)$ of system's being at time $(t+\Delta t)$ in state X_j will be equal to:

$$P_j(t+\Delta t) = P_j(t)\cdot\left[1 - l_j(t)\cdot\Delta t\right] + \sum_{i=1}^{n} P_i(t)\cdot l_i(t)\Delta t\cdot q_{ij}(t),$$

where $l_j(t)\cdot\Delta t$ is the probability of action at time t and in state j;

$l_i(t)\cdot\Delta t$ represents the probability of action at time t and in state i;

$q_{ij}(t)$ denotes the probability of transition from state i to state j.

Now, due to the nature of the object under control, note that if there is a leap of any action (controlling or disturbing), it will definitely change the state of the system, and then the probabilities q_{ij} or q_{ji} automatically become equal to 1. The moments of going the system from state to state are not predefined, known or fixed that makes it possible to identify this process by the above mentioned CDS Markov process [6]. This in turn allows the Kolmogorov equation for determining the probabilities of possible states of the dynamic system (Fig. 1) to be written as

$$\begin{aligned}
\frac{dP_{x1}(t)}{dt} &= -\left[l_{13}(t)+l_{12}(t)\right]\cdot P_{x1}(t) + \\
&\quad + m_{21}(t)\cdot P_{x2}(t) + m_{31}(t)\cdot P_{x3}(t); \\
\frac{dP_{x2}(t)}{dt} &= -\left[l_{23}(t)+m_{21}(t)\right]\cdot P_{x2}(t) + \\
&\quad + l_{12}(t)\cdot P_{x1}(t) +_{32}(t)\cdot P_{x3}(t); \\
\frac{dP_{x3}(t)}{dt} &= -\left[m_{32}(t)+m_{31}(t)\right]\cdot P_{x3}(t) + \\
&\quad + l_{23}(t)\cdot P_{x2}(t) + l_{13}(t)\cdot P_{x1}(t),
\end{aligned} \tag{1}$$

at the normalizing condition $P_{x1}(t)+P_{x2}(t)+P_{x3}(t)=1$ and initial conditions $P_{x1}(0)=1$, $P_{x2}(0)=0$, $P_{x3}(0)=0$.

In this system of equations, for the general case, the intensities of electrical mode disturbances are indicated by $l_{ij}(t)$, and the intensities of the regulation system responces by $m_{ji}(t)$, respectively. However, as shown by the studies performed [7–14], for most realizations of the stationary electrical modes in arc furnaces, the intensities of going the mode from state to state caused by disturbances in the AF can be assumed time independent and constant in magnitude for all transitions, that is $l_{ij}(t)=l$.

Similarly, the responses of the control system $m_{ji}(t)=m$ are identical for transitions and are time independent, especially in case the control is carried out using a high-speed circuit [12–14].

Taking this into consideration, system of equations (1) will be written as follows:

$$\begin{aligned}
\frac{dP_{x1}(t)}{dt} &= -2P_{x1}(t)\cdot l + \left[P_{x2}(t)+P_{x3}(t)\right]\cdot m; \\
\frac{dP_{x2}(t)}{dt} &= -P_{x2}(t)\cdot(l+m) + P_{x1}(t)\cdot l + P_{x3}(t)\cdot m; \\
\frac{dP_{x3}(t)}{dt} &= -2P_{x3}(t)\cdot m + \left[P_{x2}(t)+P_{x1}(t)\right]\cdot l,
\end{aligned} \tag{2}$$

at the same initial and normalizing conditions.

Applying the Laplace transform to solving the resulting system (2)

$$sP_{x1}(s) = -2l\,P_{x1}(s) + mP_{x2}(s) + mP_{x3}(s)\;;$$

$$sP_{x2}(s) = -(l+m)P_{x2}(s) + l\,P_{x1}(s) + mP_{x3}(s)\;;$$

$$sP_{x3}(s) = -2mP_{x3}(s) + l\,P_{x2}(s) + l\,P_{x1}(s)\,,$$

and considering the normalizing condition

$$P_{x1}(s) = \frac{1}{s} - P_{x2}(s) - P_{x3}(s),$$

one obtains a system of equations with regard to two unknowns $P_{x2}(s)$ and $P_{x3}(s)$:

$$sP_{x2}(s) = -(l+m)P_{x2}(s) + $$
$$+ l\left[\frac{1}{s} - P_{x2}(s) - P_{x3}(s)\right] + mP_{x3}(s);$$
$$sP_{x3}(s) = -2mP_{x3}(s) + l\,P_{x2}(s) + $$
$$+ l\left[\frac{1}{s} - P_{x2}(s) - P_{x3}(s)\right].$$

After simple transformations, one obtains expressions for $P_{x3}(s)$ and $P_{x2}(s)$ in the form of functions from the Laplace variable:

$$P_{x3}(s) = \frac{l}{s\cdot(s+2m+l)}\;;$$

$$P_{x2}(s) = \frac{l}{(s+2l+m)\cdot(s+2m+l)} + $$
$$+ \frac{3lm}{s(s+2m+l)\cdot(s+2l+m)}$$

and in the form of time functions

$$P_{x3}(t) = -\frac{l}{2m+l}e^{-(2m+l)t} + \frac{l}{2m+l}\;;$$

$$P_{x2}(t) = \frac{l}{m-l}e^{-(2l+m)t} + \frac{l}{l-m}e^{-(2m+l)t} - $$
$$- \frac{3lm}{(2m+l)\cdot(l-m)}e^{-(2m+l)t} - $$
$$- \frac{3lm}{(2l+m)\cdot(m-l)}e^{-(2l+m)t} + \frac{3lm}{(2m+l)\cdot(2l+m)}$$

It is not difficult to show that the probabilities $P_{x2}(t)$ and $P_{x3}(t)$ at $t = 0$ are equal to $P_{x2}(0) = 0$ and $P_{x3}(0) = 0$, respectively.

Thus, the initial conditions for the probabilities of states are satisfied, since at zero values of the second and third states probabilities, the probability of the first state is equal to 1. It is also necessary to verify that the normalizing condition will be satisfied when the transition process of the state change is complete.

Consequently, when $t = \infty$, that is, when the transition process of changes in the probabilities of states has completed, one will have the following expressions for the established values of the probabilities of states:

$$P_{x3}(\infty) = \frac{l}{2m+l}\;;$$

$$P_{x2}(\infty) = \frac{3lm}{(2m+l)\cdot(2l+m)}\;;$$

and

$$P_{x1}(\infty) = 1 - \frac{l}{2m+l} - \frac{3lm}{(2m+l)\cdot(2l+m)} = $$
$$= \frac{lm+2m^2}{(2m+l)\cdot(2l+m)}.$$

For the probability of the first state to be equal to 1 after completing the transition process, it is necessary to synthesize the density of the flow of control actions when the condition $m >> l$ is satisfied. Then

$$\lim_{npum\to\infty} P_{x3}(\infty) = \lim_{m\to\infty}\frac{l}{m+l} = 0;$$

$$\lim_{npum\to\infty} P_{x2}(\infty) = \lim_{npum\to\infty}\frac{3lm}{2l^2+2m^2+5lm} = 0;$$

$$\lim_{npum\to\infty} P_{x1}(\infty) = \lim_{npum\to\infty}\frac{lm+2m^2}{2l^2+2m^2+5lm} = 1.$$

As we can see, the normalizing condition is satisfied after completing the transition process of changing the probabilities of states.

Thus, the time dependences determined in this way for the probabilities of states enable, at a given intensity of the disturbance flow of the AF electrical mode, the synthesis of the flow intensity of the control actions which, over the optimal time of the transition process of changing the probabilities of states, will ensure the maximum probability of being the electrical mode of the furnace in the first state.

3. Conclusions

The practical use of the proposed theoretical principles of controlling the arc furnace electrical mode, provided that the intensity of the electrical mode disturbance flow is given, will enable the intensity of the flow of control actions to be operatively synthesized that will ensure the optimum speed of dynamics of the transition process of changing the probabilities of the states, and thus, the maximum probability of being the electrical mode of the furnace in the first state.

The latter will make it possible to increase the operating time of an arc furnace at the best rates of electrotechnological efficiency, and, thus, to comprehensively improve the indicators of electro-technological efficiency, averaged in over the full interval of melting. Obtaining the concrete values of electro-technological efficiency indicators will be the subject of further stochastic research.

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ПРЕДСТАВЛЕННЯ ЕЛЕКТРИЧНОГО РЕЖИМУ ДУГОВИХ СТАЛЕПЛА-ВИЛЬНИХ ПЕЧЕЙ МОДЕЛЛЮ ЗМІНИ СТАНІВ І ЗНАХОДЖЕННЯ ЙМОВІРНОСТЕЙ ЦИХ СТАНІВ

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Опрацьовано математичні основи синтезу потоку керуючих впливів, за якого оптимізується процес переве-

дення електричного режиму дугової сталеплавильної печі в заданий стан в умовах, відповідних поточним станам печі потоків збурень електричних режимів. Практичне використання запропонованої математичної моделі зміни станів дасть змогу оперативно синтезувати інтенсивність потоку керуючих впливів, що дасть можливість отримати оптимальну швидкодію регулювання динаміки перехідного процесу зміни ймовірностей станів, і, тим самим, досягти максимальної ймовірності знаходження електричного режиму в печі в необхідному електротехнологічно обґрунтованому стані.

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