ELEKTROTEHNIŠKI VESTNIK 88(1-2): 49-53, 2021
ORIGINAL SCIENTIFIC PAPER

Analysis of a modified arc length control law for electric arc furnaces

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Abstract. Electric Arc Furnaces (EAF) are powerful electro-technological installations. Their electric power ranges from 1 MVA in arc furnaces of a small capacity to more than 175 MVA in modern high-power furnaces with a capacity exceeding 200 tons. The main indicator of their energy efficiency, i.e. the amount of the electricity consumed per ton of molten steel, largely depends on the quality of the automatic control system (ACS) of the arc length, which is characterized by the speed and level of fluctuations of electrical disturbances, i.e. dynamics quality. The higher the speed and the smaller the oscillations (ideally non-oscillating, i.e. aperiodic, nature of the arc length deviations), the shorter the time of the perturbation control, and, hence, the less unproductive electricity losses in the power supply network and the short network of the arc furnace itself. Therefore, the development of solutions to improve the existing systems to control the arc length, which in electrometallurgy are called the arc power controllers, in order to increase their speed and improve the reaction to perturbations, is important because, given the significant installed capacity, it will save a considerable amount of electricity and, accordingly, reduce the cost per ton of molten steel and improve other energy efficiency indicators. The paper proposes an improved mathematical model of the modified arc length control law and creates a Simulink model of the power-supply system and electric mode coordinates ACS of an DSP-200 furnace. The results, obtained with the Simulink model, confirm an improvement of the dynamics indicators when working under the influence of perturbations, which is a necessary condition for a complex improvement of the EAF energy efficiency indicators.

Keywords: arc furnace, fuzzy inference system, electric mode, electric arc, computer model

Regulacije dolžine loka elektroobločnih peči

Električne obločne peči (EAF) so zmogljive elektrotehnološke naprave, katerih moč se giblje od 1 MVA v pečeh majhne zmogljivosti do več kot 175 MVA v sodobnih pečeh z visoko močjo. Glavni kazalnik njihove energetske učinkovitosti je količina porabljene električne energije na tono staljenega jekla, ki je v veliki meri odvisna od kakovosti avtomatskega krmilnega sistema. Višja je hitrost in manjše je nihanje, krajši je čas za regulacijo motenj. Izboljšava obstoječih sistemov za nadzor dolžine obloka je pomembna, saj bomo lahko tako prihranili znatne količine električne energije, zmanjšali stroške staljenega jekla in izboljšali preostale kazalnike energetske učinkovitosti. V tem članku predlagamo izboljšavo matematičnega modela za regulacijo dolžine loka. Eksperimentalni rezultati so potrdili izboljšanje kazalnikov energetske učinkovitosti.

1 INTRODUCTION

In the world of electrometallurgy, advanced technologies for melting high-alloy steels and precision alloys in EAF are based on the trend of intensification of electric modes [1]. The main function of the arc steelmaking furnace is to melt the solid charge to a liquid state at the highest level of efficiency. All other technological operations are carried out outside the melting space of the furnace, in the so-called ladle. This decision is dictated by the low electro-technological efficiency of the arc furnace in the technological periods of reduction and oxidation of the melt, as well as the nature of the electrical load at the stage of melting the charge created by a three-phase arc system, which is extremely dynamic, random, nonlinear and asymmetric. Given this, as well as the significant installed capacity of the EAF power equipment and the current trend of intensification of the EAF electrical mode (EM) at the stage of melting the charge, the task of creating new and improving the existing systems for automatic control of a three-phase arc lengths is the main strategy. In [2] and

Received 12 August 2020
Accepted 18 January 2021

[3], increasing the EAF productivity, reducing the cost of molten steel and improving its quality indicators are discussed.

2 Analysis of the previous research and publications

The existing electrode position systems used in EAFs of different tonnages and installed power equipment are based on the use of different models of the arc-length control law and differ in the system solutions with unique properties and energy efficiency. This provides certain advantages and disadvantages in the context of the obtained values of the energy efficiency indicators in various EM states (in various modes of arc combustion) and in various technological stages of melting [4-8].

In [4-8], the indicators of various laws (differential, current, voltage, impedance and admittant laws) of arc lengths control are investigated and analyzed. Results of a model and experimental studies of existing furnaces show that in some cases, certain control laws are better, and in other cases, control of the three-phase arc lengths is accompanied by worse dynamics, energy efficiency and reliability. Therefore, an approach is needed, enabling adaptation to different circumstances. Following the above, the goal of the paper is to implement a new, more efficient arc-length ACS.

3 The goal of the paper

The goal of the paper is to develop an engineering approach to an automatic adjustment of a three-phase arc length enabling a dynamic automatic adaptation to the current EAF EM state to increase electro-technological efficiency indicators and electromagnetic compatibility of the arc furnace and electric network.

An appropriate approach in this sense is to use a fuzzy control methodology, which enables implementation of a complex dynamic system to handle random nonstationary parametric and coordinate perturbations with a complex mathematical description and significant nonlinearities.

The focus of the paper is to investigate and design the structure of the arc-length control system with the proposed fuzzy model of the electric mode mismatch signal (control errors), perform comparative studies of the arc-length control quality indicators of the existing and proposed fuzzy model of the EM mismatch control signal generation. Then, based on model research results, conclusions are drawn on the efficiency of using the model of a fuzzy control adaptive to EM to obtain a high dynamic stabilization accuracy of electric coordinates of the EAF under the action of random phase-asymmetric parametric and coordinate perturbations in the process of electric steelmaking.

4 Study results

To increase the level of adaptation, the paper proposes a fuzzy model of the control law in which the control signal has a higher level of concordance to the current EM state and, as a result, improves the dynamics under the influence of electric mode perturbations.

The proposed modified fuzzy law (model) of the arc length control adapts the control process to the current arc-gaps state (arc length in each phase). It is based on the idea of separate (adaptive) use of standard laws (i.e. differential and voltage laws) at various states of the electric mode, in which these laws show their best capabilities.

The functional dependence describing the proposed modified law of the electrode movement control signal formation is given by the expression:

$$U_{\mathbf{c}}^{l_a}(U_a, I_a) = k \cdot U_{r.\mathbf{1}}(U_{\mathbf{a}}, I_{\mathbf{a}}) + (1-k) \cdot U_{r.\mathbf{3}}(U_a), \quad (1)$$

where $k \in [0,1]$ is a fuzzy correction (weight) coefficient calculated with the fuzzy model; $U_{r.\mathbf{1}}(U_a, I_a) = a \cdot U_a - b \cdot I_a$ is a model of the differential law;

$U_{r.3}(U_a) = k \cdot (U_a - U_{a.set})$ is a model of the voltage law.

Due to this combination, a modified law of the arc lengths control is obtained, which improves the control autonomy and, at the same time, provides more reliable arc ignition in the modes of extreme perturbations (short-circuits, arc-extinctions). It is proposed to perform a smooth transition from the voltage law to the differential law and vice versa as a function of arcs EM state changing on the basis of the fuzzy logic principles. It is proposed to identify the EM state in each phase using the current voltage value on the arcs because the voltages on the arcs do not depend on the arc currents and uniquely identify the EM states.

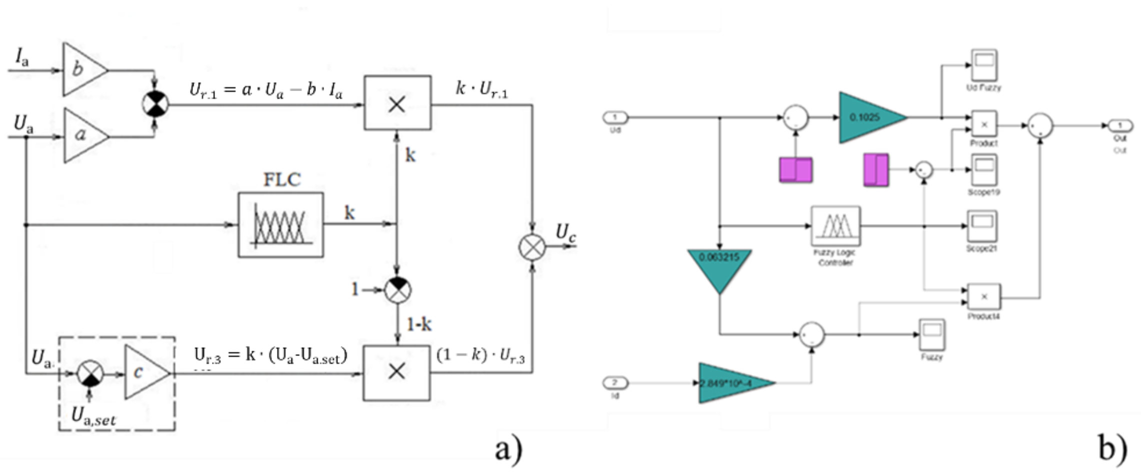

Figure 1. Scheme of a mismatch-generating signal for EM according to the modified law (1): a functional block diagram (a), a Simulink-model (b)

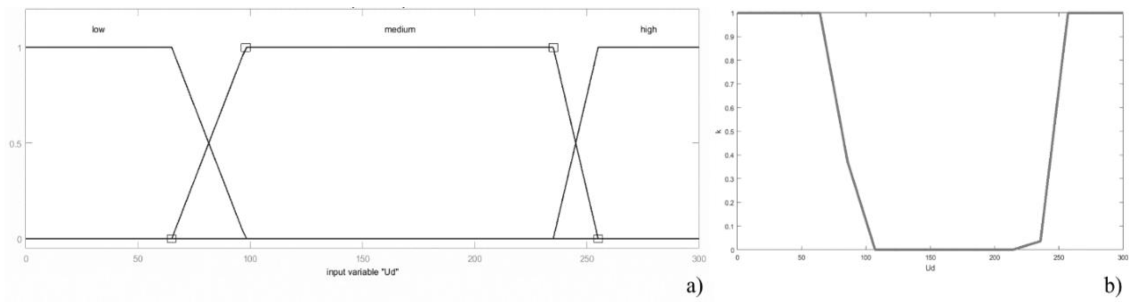

Figure 2. Membership function for a fuzzy set (a); the obtained input /output dependency $k(U_a)$ of the modified Takagi-Sugeno fuzzy model (b)

To form control signal $U_{\mathbf{c}}^{l_a}(U_a, I_a)$ for the electrodes movement based on the EM mismatch signal $U_r^{l_a}(U_a, I_a)$, obtained with the model of the adaptive fuzzy modified law (1), we developed a block diagram and its structural Simulink model (Fig. 1), the input signals of which are the current values of voltage U_a and current I_a of the arc, and the output is the EM mismatch signal $U_r^{l_a}(U_a, I_a)$.

It is proposed to implement a fuzzy model to identify the combustion mode (state) of an EAF three-phase arc using the fuzzy inference system (FIS) of the Takagi-Sugeno type (Fig. 1,a). The FIS input linguistic variable is the violation $\mathbf{U_a}$, and the output signal is fuzzy correction (weight) coefficient k. The description of fuzzy sets “short”, “medium” and “long” arc of input linguistic variable U_a is performed by three terms: low, medium and high, respectively. For them, the trapezoidal membership functions are chosen (Fig. 2, b).

To implement an adaptive to the changes in the EM states fuzzy model of forming the mismatch signal $U_r^{l_a}(U_a, I_a)$ and on its basis the electrodes movement control signal $U_{\mathbf{c}}^{l_a}(U_a, I_a)$, the FIS fuzzy output system uses the following basic fuzzy product rules:

1. if U_a ∈ low, then *k*=1 {1};
2. if U_a ∈ medium, then *k*=0 {1};
3. if U_a ∈ high, then *k*=1 {1}.

The study of the efficiency of the proposed modified fuzzy law of the arc length control is performed on the three-phase instantaneous coordinates Simulink model of the arc length control adapted to the parameters of the arc furnace of the DSP-200 type with a typical arc length controller ARDM-T-12 [11,12]. In each phase of the arc length ACS, the designed Simulink-model of the offered mismatch signal formation block (Fig. 1, b) according to the modified law (1) is implemented. To study the efficiency of the differential law, the model) of the mismatch signal formation differential law $U_{r.\mathbf{1}}(U_a, I_a)$. is used with the Simulink ACS model, instead of the model (1) .

The control dynamics of deterministic perturbations (single and consecutive single asymmetric perturbations) are studied with the designed Simulink-model during the EM ACS operation with differential and proposed modified fuzzy control laws for the

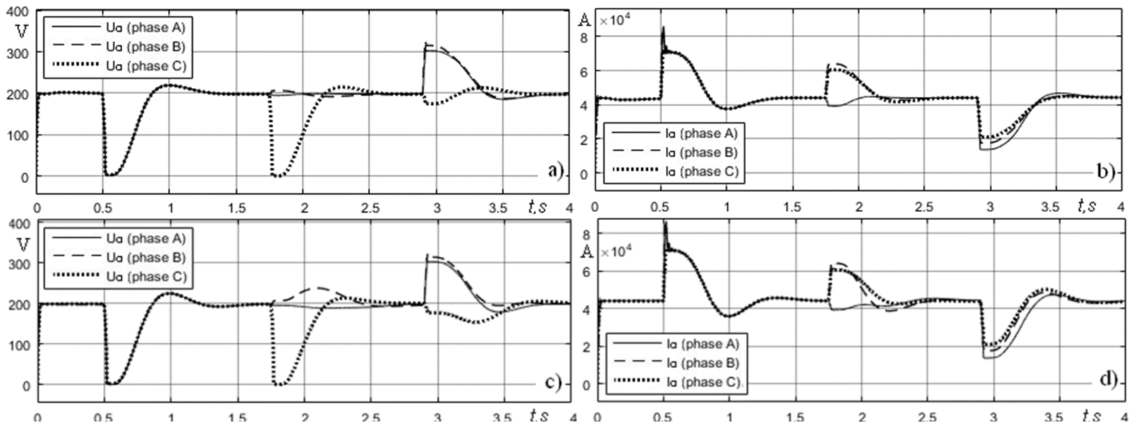

Figure 3. Time dependencies of the voltage and the current of DPS-200 furnace during the deterministic perturbations influence: (a), (b) – fuzzy model, (c) and (d) differential model.

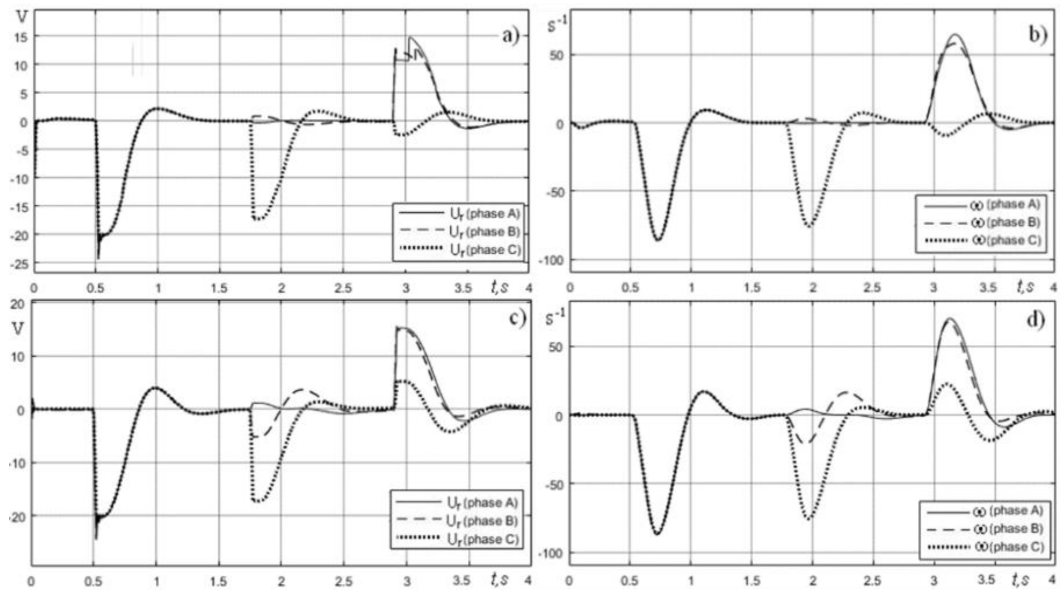

Figure 4. Time dependencies of the $U_{rj}(t)$ mismatch signals and speed : (a), (b) – fuzzy model; (c), (d) differential model.

parameters of DSP-200 arc furnace. Figure 3 shows the obtained dynamic processes when testing the deterministic perturbations sequence: symmetric three-phase operational short circuit (SC) for $t\in[0.5\text{-}1.75]$ s; single-phase SC in phase C for $t\in[1.75\text{-}2.8]$ s and state close to arc-extinction (AE) in phases A and B for $t\in[2.8\text{-}4]$ s. Figure 4 shows the time dependencies of the mismatch voltage $U_{\mathbf{c}}^{l_a}(U_a, I_a)$ change and the electrodes movement motor speed during these deterministic perturbations.

The analysis of the received processes during the deterministic perturbations influence shows the efficiency of the proposed modified control law of an EAF arc lengths. Its use increases the control speed during such perturbations. The control time of the deterministic perturbations with the use of the modified law is reduced by 20-25%. The analysis of time dependencies $U_r^{l_a}(U_a, I_a)$ and **ω(t)** (Fig. 4) shows that during the operation of the proposed modified fuzzy law, the control of arc length perturbation occurs only in the phases where there is a perturbation and in phases where there are no deviations of arc lengths from the set values, mismatch voltage $U_r^{l_a}(U_a, I_a)$ and electrode motor speed are zero, i.e. there are no erroneous movements of the electrodes. In other words, when using the modified law, there is a high level of phase-by-phase autonomy of the detection and control of deterministic perturbations. It is well known that this feature has a positive effect on reducing the variance of the EM coordinates, which, in turn, reduces the power losses in power elements of a three-phase arc system (in a short network), arc steelmaking furnace and power supply network, and increases the arc furnace energy conversion efficiency, raises the power factor (i.e. reduces the reactive power consumption), which further reduces the deviation and fluctuations of the mains voltage.

5 CONCLUSION

A modified law to control the arc lengths of the electric furnaces is proposed, based on the principles of the fuzzy logic. The law combines the use of the differential and voltage laws in the process of the perturbation control.

A functional scheme of the EM mismatch signal formation for the realization of the modified law of an EAF three-phase arc system arc length control is created.

The developed law of the arc length control is implemented in a Simulink model of the power supply system and EM coordinate control of a DSP-200 furnace with a standard arc power controller of the ARDM-T-12 type.

The dynamics is studied on a three-phase instantaneous coordinates Simulink-model of a power supply system and an arc length ACS of an EAF with a fuzzy model of an EM mismatch signal of the DSP-200 furnace.

The analysis results of the obtained quality indicators of the deterministic perturbations control dynamics show a decrease in the time of perturbations control for the EM ACS structure which uses the proposed mathematical model of the EM mismatch signal.

The developed model of the modified control law of the EAF arc lengths is simple in terms of its circuit implementation and reliable for arc ignition and is ready to be used in EAFs of any capacity, demanding no considerable capital investment cost.

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