Automatic control system development and implementation for melting in electric arc furnaces

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Abstract. Automated control systems for arc steel-melting furnaces feature a number of disadvantages and limitations with respect to complete control of technological process. The issues of automation of state-of-the-art metallurgical plants are considered. The main directions of studies of arc furnaces thermal state are detected. Studies of factor changes in the main technological parameters of ASMF-90 are carried out. The necessity of introducing the automated control over arc steel-melting furnaces melting process is substantiated. On the base of the process study, a method for arc steel-melting furnaces thermal state monitoring is proposed. A project is proposed for a modernized automatic control system for an arc steel-melting furnace operated at the modern Russian enterprise under consideration.

1. Introduction
As a rule, arc steel-melting furnaces (ASMF) feature an intermittent operation cycle, which has a significant effect on the lining materials of the furnace shaft. A typical arc steel-melting furnace ASMF-90, operated at the Russian metallurgical plant under consideration, is a batch furnace. The steel-melting cycle in an arc furnace is 50-55 min, and the metal temperature reaches 1,620-1,630 ºС. After pouring the metal, the lining temperature decreases down to 700-800 ºС. Such temperature drops negatively affect the condition of the furnace lining, since microcracks, changes in joints thickness, as well as chips and fractures occur. Moreover, the features of ASMF operation affect the thermophysical properties of lining elements themselves (metallization and slagging), and, therefore, change the heat balance of the unit, determining the necessity for constant adjustment of the arc power. ASMF efficiency and the amount of energy consumed directly depend on the heat losses occurring through a furnace lining [1]. As a result, these factors lead to a change in the shape of furnace working space and a decrease in its productivity.

On modern furnace units, the technical condition of the lining is mainly determined through visual inspection of the outer surface, at that, the data of thermal field mathematical simulation for changing the arc power are not used [2]. The existing methods of ASMF control and the level of automation do not correspond to the state-of-the-art trends in development of technology and physicochemical conditions of multicomponent alloys melting processes, which leads to premature failure of the electrodes and lining of furnaces, as well as a large number of defects with poor production of suitable products.

The condition of lining directly depends on the effective control of main source of heat in an arc steel-melting furnace, namely the electric arc. Temperature in furnace is controlled once at the end of
m Melting process in order to determine the metal readiness degree, and the electric arc is controlled using the impedance method, which does not allow for the temperature in the furnace to be considered [3].

Thus, the furnace thermal state control during the melting process and the effective control of arc steel-melting furnace are the urgent tasks for the metallurgical industry, since these issues are not resolved in full at present.

2. Experimental part
A series of experiments was conducted at the Russian metallurgical plant under consideration, in order to determine coefficient value of ASMF-90 furnace refractoriness, depending on thermophysical properties of lining materials.

In order to assess the arc voltage influence on the furnace lining, the refractoriness coefficient was used.

Refractoriness coefficient \(C_R\) is a factor determining arc effect on refractories. The refractoriness coefficient is usually calculated using the following formula [4]:

\[
C_R = \frac{V_{arc}^2 \cdot I}{d^2}, \quad \text{kJ/W/cm}^2
\]

where \(V_{arc}\) is the arc voltage, V.
I is the current supplied to the electrode, kA;
\(d\) is the distance from the arc to the refractory part of furnace (216.5 cm).

Thermal conductivity coefficient was used to determine the heat loss through the lining [4].

As a result of processing of the data obtained during the industrial experiment, the refractoriness coefficient for ASMF-90 furnace lining was calculated according to formula 1.

\[
C_R = \frac{350.0^2 \cdot 56.2}{216.5^2} = 146.9, \quad \text{kJ/W/cm}^2
\]

The graph of refractoriness coefficient dependence on arc voltage changing is presented in figure 1. The graph of refractoriness coefficient dependence on voltage changing when switching steps of transformer is presented in figure 2.

**Figure 1.** Graph of refractoriness coefficient dependence on arc voltage changing.
Figure 2. Graph of refractoriness coefficient dependence on voltage changing when switching steps of transformer.

When analyzing the graphs of arc voltage changes (figure 1 and figure 2) during the metal melting, one can see that the average arc voltage is approximately 350 V. At that, the arc length is approximately equal to 350 mm. On the basis of this fact, the slag level on the melt surface should be at least 400 mm in order to completely hide the arc, thereby reducing the degree of its influence on the lining. Therefore, the average value of refractoriness coefficient for one melting is $146.9 \text{ kV} \cdot \text{W/cm}^2$, with the maximum allowable coefficient for the arc furnace of $120.0 \text{ kV} \cdot \text{W/cm}^2$. Thus, one can conclude that refractoriness coefficient depends on the arc current in direct proportion, which is also confirmed by the results of calculation using the formula 1.

3. Practical use of research results
In order to monitor and control the temperature mode and its thermal state throughout the entire volume of the metallurgical unit (ASMF), a software algorithm as a part of the Schneider Electric application package was developed. In order to collect additional data and expand information about the process, the built-in thermocouples fix the temperature value depending on change of arc length, degree of charge heating and melt in furnace shaft. A regulator matches the values of the lining temperature from all the measurement points and sends a signal to the actuator controlling the change of electrode positions. In case if during operation the thermophysical properties of lining decline or the furnace working space change, a correction factor is introduced so that the calculated temperature values coincide with the actually measured data [5]. ASMF lining temperature profiles are shown in figure 3.

On the basis of this algorithm, a control system for indicators of ASMF-90 furnace thermal mode and its use to stabilize the technological melting mode of multicomponent charge were developed [6-7].
It is known that in order to ensure a given control performance during process control system operation in automatic control systems for non-stationary objects, it is necessary to provide a targeted change in the dynamic properties of a control device so as to compensate for undesirable changes in the control object properties [6]. An effective way to deal with this issue is to use the regulator algorithms adaptation, i.e. to change the regulator parameters when changing the object properties [8,9,10]. The schematic structure of an adaptive process control system is shown in figure 4.

Figure 3. ASMF lining temperature profiles.

Figure 4. Structural diagram of adaptive process control system for ASMF temperature monitoring.
The adaptation unit in the proposed option is developed on the basis of an algorithm for all ASMF parameters monitoring, including the additional ones (figure 5). In accordance with this algorithm, a correction factor should be determined [11]. Further, according to the correspondence table, the impedance should be chosen to define the regulator setpoint [12,13,14].

The model of this control system was implemented in the Simulink environment of Matlab 2014b software package.

**Figure 5.** Process control system for ASMF.

One can see that it is possible to speed up data transfer to control the magnitude of arc, considering the temperature differences when the thermal field in the melt zone is changing. This allows one to control the furnace thermal state during melting process and to increase the efficiency of arc steel-melting furnace control.

4. **Conclusions**

The issues of steel-melting control are analyzed by the example of the Russian metallurgical plant. Studies were carried out and the necessary experimental data were obtained for further work. A plan for a stepped resolution of the existing automation issues has been developed. An algorithm for controlling ASMF-90 arc steel-melting furnace thermal state is presented. On the base of this algorithm, a modernized automatic process control system was developed and proposed.

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