Model Predictive Control Application in the Energy Saving Technology of Basic Oxygen Furnace

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Abstract— **In today's conditions of development, maximization of profitability and ensuring technological safety of metallurgical production, the tasks of developing resource-saving technological modes of steel smelting are urgent. The fulfilment of the condition for the simultaneous achievement of the desired chemical composition and temperature of the metal is ensured by controlling the oxygen consumption and the position of the oxygen impeller lance, therefore solving the problem of managing the blasting of the converter bath is the main task.**

The mathematical modelling of the bath purge during steel smelting for energy-saving technology is executed. The method for solving Model Predictive Control with quadratic functionality in the presence of constraints is given. The algorithms of work aimed at reliability of equipment operation and energy saving are introduced.

Implementation of the described solutions will contribute to improving efficiency and reliability of equipment, increasing the proportion of scrap and reducing the melting period without changing of technological process.

Keywords— Model Predictive Control, Basic Oxygen Furnace, Predictive Model, Linear-Quadratic Functional, Optimal Control, Energy Saving.

I. Introduction

Automation of control of technological processes and production plays an important role in continuous increase of output of finished products. The intensification and complication of technological processes, increasing the capacity of units and increasing the quality requirements of finished products make it impossible to manage the units without improving the structure of automatic control systems.

Steel production is a complex process that requires the use of a complex of technological, energy and transport equipment, each of which requires appropriate automation. Special control automatic control systems are being developed to control steelmaking workshops, which are implemented at all stages of steel production.

Today, basic oxygen furnace (BOF) is the most popular steel production in the world. Automation of the BOF involves obtaining high quality steel, which is possible while achieving the desired chemical composition and metal temperature [1]. This condition is ensured by controlling the flow of oxygen and the position of the lance of the oxygen converter, so solving the problem of controlling the purge of the converter bath is the main task. That is why the task of implementing modern control methods in the conditions of stochasticity, non-stationarity and limitations of technological processes is an urgent problem today. One modern advanced control method is control theory using predictive models, such as Model Predictive Control (MPC). Model Predictive Control is an optimal control strategy based on numerical optimization. Future control inputs and future plant responses are predicted using a system model and optimized at regular intervals with respect to a performance index [2].

II. The Aim and Objectives of the Study

The purpose of the work is to develop an automatic control system for basic oxygen furnace-smelting, which would provide the specified quality indicators in conditions of unsteadiness of the rate of decompression and perturbations associated with changes in oxygen consumption for purging and introduction of loose. To achieve the objective, the following tasks were formulated:

- to study the dynamic properties of the process of changing the rate of decarbonization of metal;
- obtain a predictive model of the degree of carbon oxidation to the carbon dioxide of the oxygen-converter process;
- to solve the problem of MPC-control with quadratic functional in the presence of restrictions;

III. Mathematical Model of Oxygen Converter Processre

The transient process of changing the rate of decarburization from changing the distance of the lance to the level of a quiet bath is described by the transfer function (1) of the form [3]:

$$W_{v_c}(s) = \frac{k_{v_c}}{T_{v_c} s + 1}, \quad (1)$$

where k_{v_c} $t/h \cdot m$ - the transmission coefficient through the channel distance of lance to the level of a quiet bath - the rate of decarburization; T_{v_c}, s - time constant.

The time constant (2) is non-stationary and also depends on the melting period. It can be described functions [3]:

$$T_{v_c}[s]=\begin{cases}1{,}143+4{,}446\cdot\tau-0{,}484\cdot\tau^2, \text{ 1 period}\\ 11{,}267, \text{ 2 period}\\ 11{,}267-4{,}446\cdot(\tau-16)+0{,}484\cdot(\tau-16)^2, \text{ 3 period}\end{cases} \quad (2)$$

where $\tau[\min]$ – purging time

Changing the rate of decarburization leads to a change in the degree of carbon oxidation to carbon dioxide in the converter cavity. This process is also described by the first-order transfer function (3) of the form [3]:

$$W_{\gamma_{CO_2}}(s)=\frac{k_{\gamma_{CO_2}}}{T_{\gamma_{CO_2}}s+1}, \quad (3)$$

where $k_{\gamma_{CO_2}}$ $\%CO_2\cdot\min/t$ is the transmission rate through the channel of the speed of carbonation - the degree of carbon oxidation to CO_2; - it is time. According to the results of experimental studies [4], the transmission rate of the channel is the carbonation rate - the degree of carbon oxidation to CO_2 is determined from the balance equation of the purge flow rate $k_{\gamma_{CO_2}}=3{,}33\ \%CO_2\cdot m/t$.

IV. MPC CONTROLLER DESIGN AND CONTROL SYSTEM MODELING

We perform the design of a quadratic-functional MPC controller with constraints using the Matlab MPC Designer package [5]. The design of the MPC controller will be performed using the mathematical model of the oxygen converter process, which is described in Section 3.

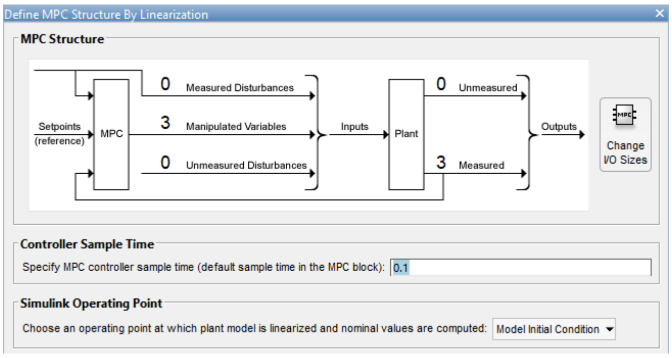

Figure 1 Description of the structure of the MPC controller

The predictive model (4) of the oxygen converter process for the second purge period of the oxygen converter process is obtained:

$$x_{i+1}=Ax_i+Bu_i,$$
$$y_i=Cx_i,$$
$$i=k+j,\ j=0,1,2...,$$

where k - tact number; $x_i\in E^n$ – the state of the object; $y_i\in E^r$ – measurement value; $u_i\in E^m$ – control action;

$$A=\begin{pmatrix}-1.613 & 0 & 0 & 0 & 0\\ 0 & -0.0887 & 0 & 0 & 0\\ 9.677 & 0 & -0.2924 & 0 & 0\\ 0 & 0 & 0 & -0.2 & 0\\ 0 & 0.3426 & 0.00146 & 0 & -0.466\end{pmatrix},$$

$$B=\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{pmatrix}, \quad (4)$$

$$C=\begin{pmatrix}9.677 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 1.522\\ 0 & 0 & 0 & 0.11 & 0\end{pmatrix}$$

According to the MPC strategy, the behaviour of the object is predicted and the resulting structure is optimized to find the optimal control of the oxygen converter. The obtained optimal control is applied at the current step, after which the forecast horizon shifts and the described sequence of actions is repeated [6]. The approach takes into account the constraints imposed on both control variables and control variables.

The simulation of oxygen transients during purging for a 160-ton converter in the second purging period using an oxygen flow control algorithm aimed at ensuring the reliability of the equipment and adjusting the position of the lance by the energy-saving technology of combustion of CO to CO_2 is shown in Fig. 2.

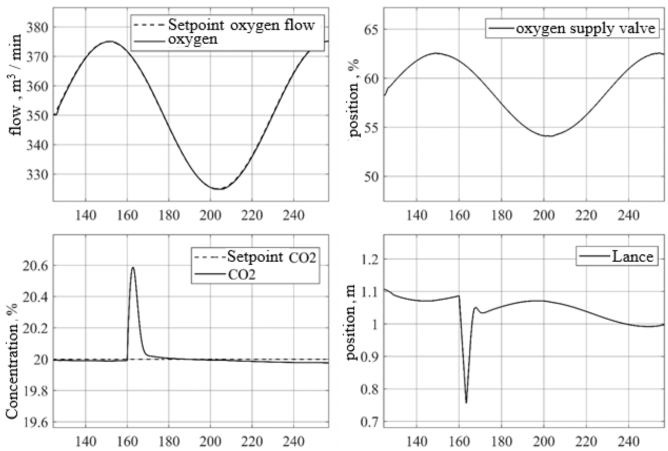

Figure 2. Front processes of the automatic control system for oxygen converter melting during the second purge period

The obtained transients of the automatic control system of the oxygen-converter process using the MPC-strategy provide the requirements to the quality of the system. The obtained transients of the system of automatic control of the oxygen-converter process using the MPC-strategy provide the requirements to the quality of the system.

V. Conclusions

During the purge of the converter bath, the control system solves the problem of synchronization of the refining and heating processes of the metal with reliable blast mode. Adjustment of the lance position is carried out according to the economic regime, based on the increased degree of combustion of CO to CO2 in the converter cavity. It is established that at a certain chemical composition of iron, the thermal regime of the process depends on the rate of decarburization, the degree of combustion of CO to CO2 and the amount of iron oxides in the slag, which, in turn, depend on the distance of the lance to the level of a quiet bath.

The decarburization process is non-stationary, described by a first-order aperiodic link, the transmission coefficient and time constant of which depends on the melting period and the purge duration. The change in the degree of supplementation of CO to CO2 is also described by the first-order aperiodic link. A mathematical model of an object in which the input value of the lance distance to the level of a quiet bath and the initial - the degree of carbon oxidation to CO2 is described by a non-stationary oscillatory link.

According to the MPC strategy, the behaviour of the object is predicted and the resulting structure is optimized to find the optimal control of the oxygen converter process. The resulting optimal control is applied at the current step, after which the forecast horizon is shifted and the described sequence of actions is repeated. In MPC control, non-linear systems of ordinary differential equations can be used as a predictive model.

The approach takes into account the constraints imposed on both control variables and control variables. The approach minimizes the functionality that characterizes the quality of the adjustment process in real time. The predicted behaviour of a dynamic object will generally be different from its actual motion. In order to work in real time, it is necessary that the solution of the optimization problem is carried out fairly quickly. The obtained transients of the control system with the use of MPC-strategy meet the set requirements for quality of operation and provide high reliability of operation.

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