MODEL PREDICTIVE CONTROL APPLICATION IN THE ENERGY SAVING TECHNOLOGY OF BASIC OXYGEN FURNACE

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Abstract. 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. The method for solving Model Predictive Control with quadratic functionality in the presence of constraints is given. Implementation of the described solutions will contribute to increasing the proportion of scrap and reducing the melting period without changing of technological process.

Keywords: model predictive control, basic oxygen furnace, optimal control, energy saving

2. Mathematical model of oxygen converter process

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]:

\[ W_c(s) = \frac{k_c}{T_c s + 1} \]  \hspace{1cm} (1)

where \( k_c \left[ \frac{t}{(h \cdot m)} \right] \) – the transmission coefficient through the channel distance of lance to the level of a quiet bath – the rate of decarburization; \( T_c \ [s] \) – time constant.

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

\[ T_c = \begin{cases} 1.143 + 4.446 \tau - 0.484 \tau^2, & 1 \text{ period} \\ 11.267, & 2 \text{ period} \\ 11.267 - 4.446(\tau - 16) + 0.484(\tau - 16)^2, & 3 \text{ period} \end{cases} \]  \hspace{1cm} (2)

where \( \tau \ [\text{min}] \) – 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]:

\[ W_{CO_2}(s) = \frac{k_{CO_2}}{T_{CO_2} s + 1} \]  \hspace{1cm} (3)

where \( k_{CO_2} \left[ \frac{\% CO_2 \cdot \text{min}^{-1} \cdot r^{-1}}{s} \right] \) 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 [5], 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 \( k_{CO_2} = 3.33 \ % \cdot \text{min}^{-1} \cdot r^{-1} \).

The two links are connected in series (4) and the transfer function of the system in which the input value of the lance distance to the level of a quiet bath and the output – the degree of carbon oxidation to \( CO_2 \):

\[ W_c(s) = \frac{k_c k_{CO_2}}{(T_c s + 1)(T_{CO_2} s + 1)} = \frac{k_{CO_2}^H}{(T_c s + 1)(T_{CO_2} s + 1)} \]  \hspace{1cm} (4)
where $k_1 \left[ \%_{CO} \cdot m^{-1} \right]$ – the transmission coefficient through the channel distance of lance to the level of a quiet bath – the degree of carbon oxidation to CO$_2$.

The system on the channel "position of the swing flap – vacuum in the caisson" has a transfer function (5):

$$W_s(s) = \frac{0.55}{5s + 1}$$  
(5)

where $W_s(s)$ – a transfer function on the channel "position of the swing flap – vacuum in the caisson".

3. MPC controller design and control system modelling

The design of a quadratic-functional MPC controller with constraints was performed using the Matlab MPC Designer package [11]. The design of the MPC controller (Fig. 1) used the mathematical model of the oxygen converter process, which is described in section 2.

The predictive model (6) of the oxygen converter process for the second purge period of the oxygen converter process is obtained:

$$x_i = Ax_i + Bu_i,$$
$$y_i = Cx_i,$$

$i = k + j, j = 0, 1, 2, ...$,

where $k$ – tact number, $x_i \in E^n$ – the state of the object, $y_i \in E^m$ – measurements, $u_i \in E^m$ – control action,

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

B = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1 \\
0 & 0 & 0
\end{bmatrix},

C = \begin{bmatrix}
9.677 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1.522 \\
0 & 0 & 0 & 0 & 0.11
\end{bmatrix}
$$  
(6)

The dynamic properties of the actuators was introduced into the MPC-controller as the constraints on the input values (Fig. 2).

The quality of control is characterized by a linear-quadratic functional (7):

$$J_k = J_k(\tilde{y}, \tilde{u}) = \sum_{j=1}^{P} \left[ (y_{i+j} - r_{i+j})^T R_{k, i+j} (y_{i+j} - r_{i+j}) + u_{i+j}^T Q_{k, i+j} u_{i+j} \right]$$  
(7)

where $R_{k, i+j}$ and $Q_{k, i+j}$ – positively defined symmetric matrices.

Auxiliary vectors (8):

$$\tilde{y} = (y_{i+1}, y_{i+2}, ..., y_{i+P})^T \in E^p$$
$$\tilde{u} = (u_{i}, u_{i+1}, ..., u_{i+P-1})^T \in E^p$$  
(8)

Given that the movement of the system (6) on the clock is only determined, then, the problem of optimization (9) with respect to the functional (7) can be formulated:

$$J_k(\tilde{u}) \rightarrow \min_{\tilde{u} \in E^p}$$  
(9)

The solution to problem (9) found, the functional (7) presented in the form (10):

$$J_k = J_k(\bar{u}) = \left( \bar{y} - \bar{r} \right)^T R \left( \bar{y} - \bar{r} \right) + \bar{u}^T Q \bar{u}$$

where

$$y_{k+1} = C_{k+1} x_{k+1} + CB_{k+1} u_{k+1}$$

where $u_{k+1}$ = $C_{k+1} x_{k+1}$ + $CA$ $x_{k}$ + $CAB$ $u_{k}$ + $CB_{k+1}$

e.t.c. $y_{k+2} = C_{k+2} x_{k+2} + CA^2 x_{k} + CA^2 B u_{k} + C B_{k+1}$

$\Rightarrow \bar{y} = L x_k + M \bar{u}$, where

$$L = \begin{bmatrix}
CA & \ldots & 0 \\
CA^2 & \ldots & \ldots \\
\ldots & \ldots & \ldots \\
CA^P & \ldots & \ldots \ldots & CB
\end{bmatrix},

M = \begin{bmatrix}
CB & 0 & \ldots & 0 \\
CAB & CB & \ldots & 0 \\
\ldots & \ldots & \ldots & \ldots
\end{bmatrix}$$

$$J_k = J_k(\bar{u}) = \left( L \bar{x}_k + M \bar{u} - \bar{r} \right)^T R \left( L \bar{x}_k + M \bar{u} - \bar{r} \right) + \bar{u}^T Q \bar{u}$$

$$\frac{\partial J_k}{\partial \bar{u}} = \left[ \left( L \bar{x}_k + M \bar{u} - \bar{r} \right)^T R \left( L \bar{x}_k + M \bar{u} - \bar{r} \right) + \bar{u}^T Q \bar{u} \right] = 0$$

$$\Rightarrow \bar{u} = \bar{K} \bar{x}_k + \bar{T}$$

$$\bar{K} = \left( M^T R + Q \right)^{-1} M^T R \bar{L}, \bar{T} = \left( M^T R + Q \right)^{-1} M^T \bar{R}$$

Matrix search algorithm:

2. Using the input data in the form of matrices $R$ and $Q$ calculate additional matrices $\bar{K}$ and $\bar{T}$ from (10).
3. Select the upper blocks in size $m*n$ and $m*r$ according to the matrices $\bar{K}$ and $\bar{T}$. 

![Fig. 1. Description of the structure of the MPC controller](image1)

![Fig. 2. Constraints to input values introduced in the MPC controller](image2)
According to the MPC strategy, the behaviour of the system 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 [4]. The approach takes into account the constraints imposed on both control variables and control variables.

The simulation procedure was performed in the Matlab Simulink environment. An algorithm for solving the equations ode23s (stiff / mod. Rosenbrock) was chosen with variable-step change. The absolute and relative accuracy of the calculations is 0.0001.

For a control system of oxygen consumption, a perturbation of a task of 15 m³/min (Fig. 3) relative to the nominal value of oxygen consumption is typical during purging. The obtained system quality indicators are shown in Table 1.

<table>
<thead>
<tr>
<th>Quality indicators</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static error</td>
<td>0</td>
</tr>
<tr>
<td>Dynamic Error</td>
<td>0.067</td>
</tr>
<tr>
<td>Adjustment time</td>
<td>8 s</td>
</tr>
<tr>
<td>The attenuation index</td>
<td>0.95</td>
</tr>
<tr>
<td>Overshoot</td>
<td>6.67%</td>
</tr>
</tbody>
</table>

For the control system of CO₂ content, the main task is the problem of stabilization (Fig. 5) in the event of disturbances: changes in the flow rate of oxygen, change in the rate of decarburation, introduction of bulk, etc. Transitions through the perturbation-output channel are shown in Fig. 4. The obtained system quality indicators are shown in Table 2.

<table>
<thead>
<tr>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static error</td>
<td>0</td>
</tr>
<tr>
<td>Dynamic Error</td>
<td>0.1%</td>
</tr>
<tr>
<td>Adjustment time</td>
<td>18 s</td>
</tr>
<tr>
<td>The attenuation index</td>
<td>1</td>
</tr>
<tr>
<td>Overshoot</td>
<td>10%</td>
</tr>
</tbody>
</table>

Transitions through the disturbances for perturbation-output channel are shown in Fig. 5. The obtained system quality indicators are shown in Table 3.

To discharge the converter gases, a small (6–50 Pa) vacuum should be maintained in the caisson above the converter. Adjustment of pressure in a caisson is carried out by influence on a rotary damper in a gas-purifying tube. For the perturbation control system there is a converter gas recovery system. The transients of the system of automatic control of the vacuum on the channel vacuum-output are shown in Fig. 6, obtained system quality indicators are shown in Table 4.
Table 4. Quality indicators of SAR vacuum in the caisson

<table>
<thead>
<tr>
<th>Quality indicators</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static error</td>
<td>0</td>
</tr>
<tr>
<td>Dynamic Error</td>
<td>0.09</td>
</tr>
<tr>
<td>Adjustment time</td>
<td>27 s</td>
</tr>
<tr>
<td>The attenuation index</td>
<td>0.91</td>
</tr>
<tr>
<td>Overshoot</td>
<td>9%</td>
</tr>
</tbody>
</table>

Transitions through the disturbances of the vacuum channel are shown in Fig. 7. The obtained system quality indicators are shown in Table 5.

Table 5. Quality indicators of SAR the disturbances of vacuum in the caisson

<table>
<thead>
<tr>
<th>Quality indicators</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static error</td>
<td>0</td>
</tr>
<tr>
<td>Dynamic Error</td>
<td>0.52 Pa</td>
</tr>
<tr>
<td>Adjustment time</td>
<td>18 s</td>
</tr>
<tr>
<td>The attenuation index</td>
<td>0.8</td>
</tr>
<tr>
<td>Overshoot</td>
<td>0%</td>
</tr>
</tbody>
</table>

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$_2$ (Fig. 8). The obtained transients of the automatic control system of the basic oxygen furnace process using the MPC-strategy provide the requirements to the quality of the system.

Fig. 7. Intersection process of the automatic control system on the vacuum channel by the gas-vacuum system in the caisson

Fig. 8. Front processes of the automatic control system for oxygen converter melting during the second purge period
4. Conclusions

An advanced process control of the refining and heating processes of the metal with reliable blast mode during the purge of the converter bath is described. The using of Model predictive control approach with taking into account the set requirements for quality of operation and provide high operations reliability is proposed. It is known 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. 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. The non-stationary of the melting processes is shown and explained. It makes the use of classical control methods irrational.

It is recommended to use the MPC strategy to solve those processes synchronization problem under physical and technical constraints. The approach minimizes the functionality that characterizes the quality of the adjustment process in real time. The predicted behaviour of a dynamic system will generally be different from its actual motion. Math models of processes are built. The decarburization process is represented as non-stationary first-order inertial transfer function, the gain 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 such model type. The non-stationary oscillatory link describes the system 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.

The behaviour of the system is predicted by MPC and the resulting structure is optimized to find the optimal control of the oxygen converter process. The approach takes into account the constraints imposed on both control variables and control variables.

In order to work in real time, it is necessary that the solution of the optimization problem is carried out fairly quickly. The proposed approach was modeled in dynamics in the corresponding software environment. The simulation results show the achievement of the required quality indicators.

References