

# Nonlinear system identification of the reduction nickel oxide smelting process in electric arc furnace

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**Abstract.** As the title implies the article describes the nonlinear system identification of the reduction smelting process of nickel oxide in electric arc furnaces. It is suggested that for operational control ratio of components of the charge must be solved the problem of determining the qualitative composition of the melt in real time. The use of 0<sup>th</sup> harmonic of phase voltage AC furnace as an indirect measure of the melt composition is proposed. Brief description of the mechanism of occurrence and nature of the non-zero 0<sup>th</sup> harmonic of the AC voltage of the arc is given. It is shown that value of 0<sup>th</sup> harmonic of the arc voltage is not function of electrical parameters but depends of the material composition of the melt. Processed industrial data are given. Hammerstein-Wiener model is used for description of the dependence of 0<sup>th</sup> harmonic of the furnace voltage from the technical parameters of melting furnace: the melt composition and current. Recommendations are given about the practical use of the model.

## 1. Introduction

Most sulphide ores have traditionally been processed using rotary kiln electric furnace (RKEF) techniques to produce a nickel matte for electrorefining. RKEF process can include the next steps: pre-treatment, drying, calcination in a fluidized-bed roaster, prereduction in a rotary kiln, smelting in electric arc furnace and, finally, electrorefining. The non-reduced calcine and the prereduced calcine from the RK charged into the electric arc furnace. Coke have been used as the reducing agent. [1, 2]

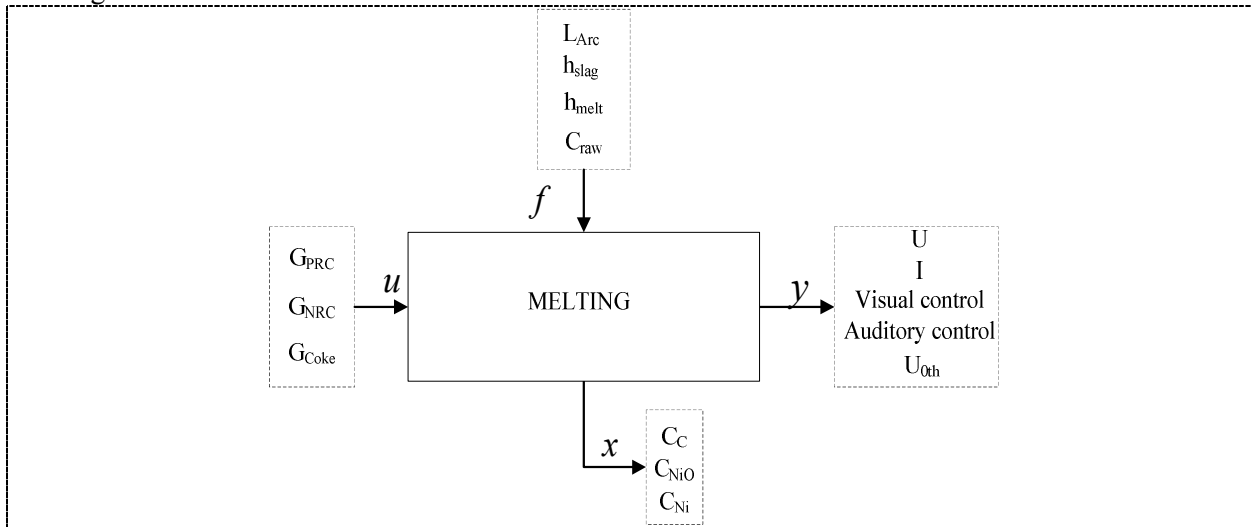
It is considered that optimal mass concentration of carbon in the reaction mass approximately equal 2.2%. It is minimize the consumption of energy for smelting. At the end of melting the carbon concentration must be equal to 0.04-0.12%. [3]

The quality control process is greatly influenced by the accuracy of determining the composition of the melt. Available methods of chemical analysis have a great time duration. As a rule, founder carries out a visual analysis of the sample to fast determinate the state of the metal in the furnace.

The process of smelting of a Nickel anode in an electric arc furnace as a control object is shown in figure 1. The model's inputs are mass flow of the components of the charge, having a pulsed characteristic. Perturbation are the change of the interelectrode distance, which depends on the position of the electrode and the height of the melt and slag; volatility of raw materials by composition. An automatic regulator of a known principle controls the position of the electrodes but, in fact, this parameter is external to the control system of technological mode of the furnace. Concentrations of melt components are considered as state variables. Outputs are electric characteristic – voltage and electrode's



current, – and data obtained by visual analysis of the metal sample and the spectral analysis of the audio signal.



**Figure 1 – The process of smelting of a Nickel anode in an electric arc furnace as a control object.**

One of ways of the EAF process control is obtaining information about processes inside the furnace from the changing of electrothermal conditions in furnace. In the arc voltage AC may be present non-zero 0<sup>th</sup> harmonic ( $U_{0th}$ ), which depends on various melting conditions, such as temperature, the shape of the arc, resistance of the reaction mass. [4]

$U_{0th}$  occurs due to electric arc mode, in which the density of the emission current of the first electrode can be more then density of the emission current of the second electrode. RMS-value of furnace's voltage during melting changes slightly because this is provided by automatic control of the position of the electrodes. At the same time,  $U_{0th}$  can be used as one of the parameters of the process for process control.

## 2. Experiment

Experimental (factory) research of process of reduction smelting was conducted in furnaces of the type RKZ-10.5. The experience was carried out measurement of phase voltages of the furnace, the measurement of current and voltage waveform at the output of the regulator the position of the electrodes. In the journal of melting was recorded charging time of all components of the charge.

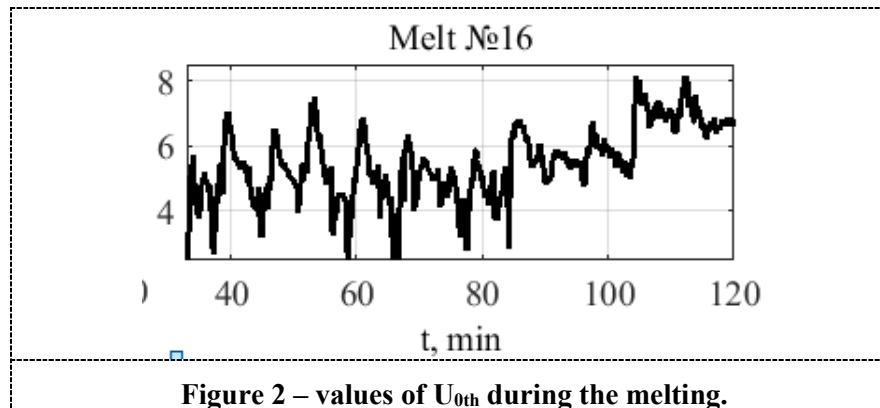
ADC USB-6008 was used for data collection. Sampling frequency was 1000 Hz. Spectral analysis of a signal performed in real time in the program developed in the LabView development environment.

## 3. Result.

### 3.1. Data processing

This research shows that value of  $U_{0th}$  equals to about 4-6 Volts in the absence of disturbances during the period of carbonization, when the prereduced calcine and the coke was charged. The value of  $U_{0th}$  decreases significantly during charging.  $U_{0th}$  increases to 7-8 Volts by the end of the period of finishing, when the calcine was charged. [5, 6]

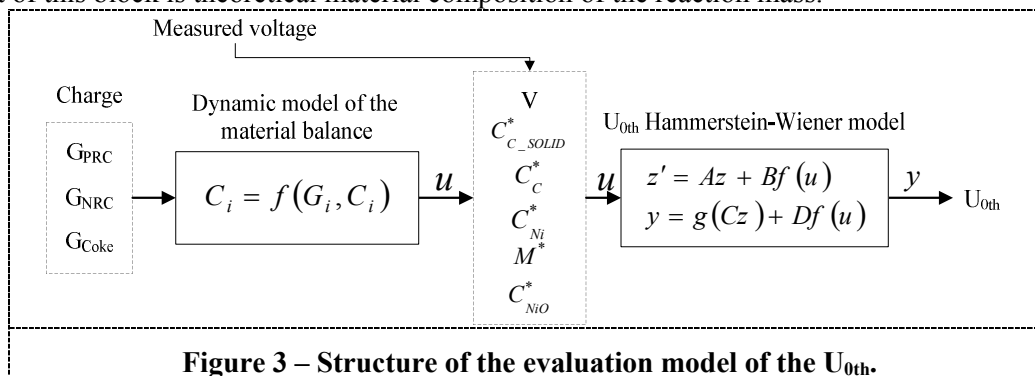
Figure 2 shows the measured value of  $U_{0th}$  for the one melt. The total number of recorded melts is 21.



**Figure 2 – values of  $U_{0th}$  during the melting.**

### 3.2. Melting process modeling

The goal of the modeling was to determine the relationship between the ratio of the components of the charge and the value of  $U_{0th}$ . In the present paper, a block of nonlinear model was used; its structural diagram is shown in figure 3. The first block of the model is a dynamic model of material balance. Output of this block is theoretical material composition of the reaction mass.



**Figure 3 – Structure of the evaluation model of the  $U_{0th}$ .**

The second part of the nonlinear block model is the simple cascade Hammerstein-Wiener model.

This model based on the calculated concentrations in the reaction mass and the measured values of voltage and  $U_{0th}$ . The model establishes a functional dependence between the value of  $U_{0th}$  and the composition of the reaction mass, and a current electrode. The resulting model has a high degree of convergence.

Hammerstein-Wiener Model belongs to the class of block-oriented models and describes a linear dynamic and a nonlinear static characteristic of the object of modeling.

The model can be described by the following equations:

$$x(t) = f(\alpha, u(t)) \quad (1)$$

$$r(t) = G(q^{-1}, \beta) \cdot x(t) \quad (2)$$

$$y_0(t) = g(\gamma, r(t)) \quad (3)$$

where  $y_0(t)$  – model's prediction of the output  $y(t)$ ,  $G(q^{-1}, \beta)$  – a linear dynamical system parametrized by delay operator  $q^{-1}$ ,  $\alpha$  and  $\gamma$  – parameters of nonlinear functions  $f$  and  $g$ . All parameters can be presented as the vector of parameters  $\theta = [\alpha, \beta, \gamma]$ . [7]

List of model's inputs:

- $u_1$  the rms-value of the phase voltage, [0; 200] V;
- $u_2$  the concentration of solid carbon (coke), [0;10] % mass.;
- $u_3$  the concentration of carbon [0;2,5] % mass.;
- $u_4$  the total mass of furnace charge, [0; 28] ton;
- $u_5$  the concentration of a nickel [0;90] % mass.;

-  $u_6$  the concentration of a nickel monoxide, [0;10] % mass.;

Model's output  $y$  is  $U_{0th}$ , [0;10] V.

The calculation of the coefficients of the model was carried out by the method of least squares. The target function was the residual sum of squares  $\sum_{i=1}^N (y_i - \hat{y}_i)^2$ . As a method of optimization was chosen as the Levenberg–Marquardt algorithm.

The model was reduced after training. The final model contains 3 inputs ( $u_1, u_2, u_5$ ) and 1 output.

The model can be described by the state space equation:

$$\begin{aligned} z_{(k+1)\Delta t} &= Az_{k\Delta t} + Bf_{k\Delta t}(u_{k\Delta t}) \\ y_{k\Delta t} &= g_{k\Delta t}(Cz_{k\Delta t}) + Df_{k\Delta t}(u_{k\Delta t}) \end{aligned} \quad (4)$$

where  $f_{k\Delta t}(u_{k\Delta t})$  – vector of functions of inputs, which are as follows:

$$x_i(t) = \begin{cases} x_i^L, & \text{npu } u_i \leq u_i^L \\ K(u_i - u_i^L) + x_1, & \text{npu } u_i^L \leq u_i \leq u_i^H \\ x_i^H, & \text{npu } u_i \geq u_i^H \end{cases} \quad (5)$$

The parameters of the function identified in the learning model are summarized in table 1.

**Table 1.** The parameters of the model

	$x_i^L$	$x_i^H$	$u_i^L$	$u_i^H$	$K$
$u_1$	-3340	-17200	54,03	92,38	-361.41
$u_2$	13100	34200	15500	23800	2.54
$u_5$	8.15	3.14	0	0.05	-104.65

Vector  $z_{k\Delta t}$  in the formula (5) is the vector of state variables,  $y_{k\Delta t}$  – model's output. Function  $g_{k\Delta t}$  has the following form:

$$g_{k\Delta t}(Cz_{k\Delta t}) = 9.9319 \cdot (10^{-5}) \cdot (Cz_{k\Delta t}) + 3.73 \quad (6)$$

State matrix, input matrix, output matrix and feedthrough matrix equal to:

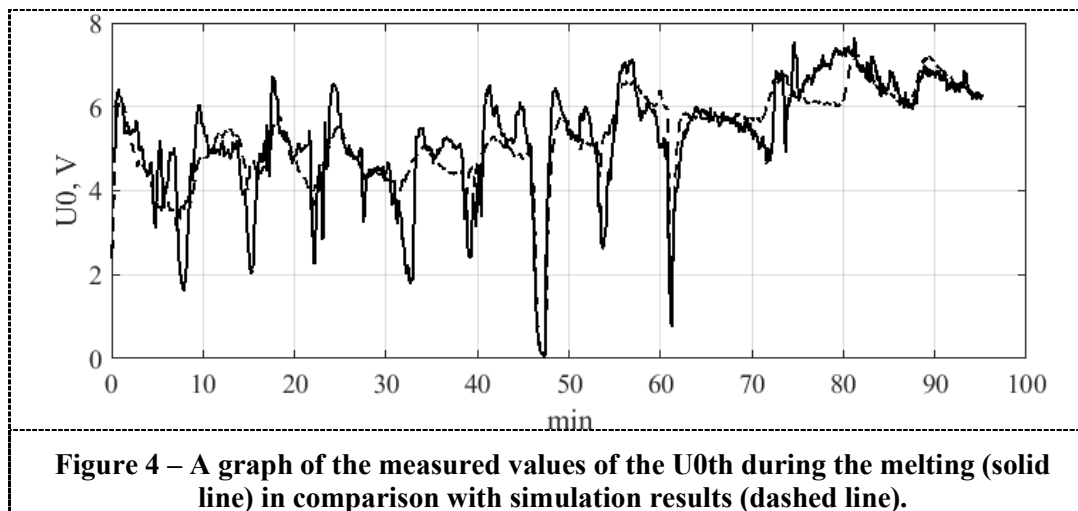
$$A = \begin{bmatrix} 0,88 & 0 & 0 \\ 0 & 0,96 & 0 \\ 0 & 0 & 0,99 \end{bmatrix}, \quad B = \begin{bmatrix} 0,94 & 0 & 0 \\ 0 & 0,98 & 0 \\ 0 & 0 & 0,99 \end{bmatrix},$$

$$C = [-0,32 \quad 0.05 \quad -75.99], \quad D = [0 \quad 0 \quad 0].$$

The resulting model has the following characteristics:

- mean squared error (MSE) equal to 0,54 V;
- mathematical expectation of the error equal to 0.004 V;
- the coefficient of determination equal to 0,52 V.

Figure 4 graphs the measured values of the  $U_{0th}$  and the values obtained during the simulation.



#### 4. Conclusions.

Zeroth harmonic of the AC voltage depends of the parameters of the arc and the properties of the melt, because furnace circuit include the arc and the melt, considered as a homogeneous reaction mass with variable conductivity. This statement can be used as the basis for determining the concentration of certain components of the melt on the value of the 0<sup>th</sup> harmonic.

The variability of the raw's composition makes inefficient use of open-loop automatic control system. Direct analysis of the composition of the melt can not be used for rapid adjustment of the charge composition.

In this regard, an interesting possibility to estimate the concentration of Nickel oxide in the melt by the proposed model. The feature of the model is that the input parameters are time-dependent functions of the mass flows of the components of the charge.

- [1] Crundwell F K 2011 *Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals* (Oxford: Elsevier) p 610
- [2] Voermann N, Gerritsen T, Candy I, Stober F and Matyas A 2004 Developments in furnace technology for ferronickel production *10th International Ferroalloys Congress* (Cape Town, South Africa)
- [3] Paulson D. L and Anable W E 1977 Smelting prerduced nickel concentrate in an electric-arc furnace *US Dep. of the interior. Bureau of mines* vol 4 p 20
- [4] Pedro A A 1993 About a nature of direct component of an electric arc phase voltage in the normal corundum furnace *Promyshlennaya energetika* vol 5 (Moscow: Energoprogress JSC) pp 28-31
- [5] Gubin V V and Firsov A Yu 2015 The using of barrier effect of the arc for the control of reductive smelting of nickel monoxide *Natural and technical science* vol.6 (Moscow) pp. 463-468
- [6] Pedro A A, Bazhin V Yu, Suslov A P, Firsov A Yu and Martynova E S 2017 Power control of the open electric arc for the electrode furnace *Steel* vol.7 (Moscow) pp. 21-23
- [7] Giri F and Bai E 2010 *Block-oriented Nonlinear System Identification* (Springer) p. 426