A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 53 2008 Issue 2

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MODEL OF ARC VOLTAGES MEASUREMENT CIRCUITS AND MEASUREMENT SYSTEM FOR THE CIRCUITS PARAMETERS IDENTIFICATION

MODEL OBWODÓW POMIARU NAPIĘCIA ŁUKU I SYSTEM POMIAROWY DO IDENTYFIKACJI PARAMETRÓW OBWODU

The signals that characterize the work of an electric arc furnace are important not only for the electric circuit power control and electrode position control but also for control of the injections of coal in the foaming slag system. Taking into account above requirements, there is important to choose proper measurement signals. Measurement only electrical signals are not sufficient for control systems. For proper control of electrodes knowledge about their positions is also important.

For data acquisition a special system was constructed. The system consists of portable computer with acquisition card, conditioning system with differential amplifiers, antialiasing filters and sample and hold circuits. The system software makes possible on-line observation of measured signals and save data to hard disk. After measurement information obtained in no-load state, three two-phase short circuits and three-phase short circuits tests were used in compensation algorithm for calculation the circuits parameters and describing real arc voltages. Positions of electrodes were calculated from recorded electrode speeds. Next all data were analysed off-line to determine arc model parameters and to define control system states. In the paper some interesting phenomena observed in furnace control system are presented.

Keywords: arc furnace, data acquisition, control system, hardware, algorithms

Sygnały, które charakteryzują pracę elektrycznego pieca łukowego są istotne nie tylko do sterowania mocą obwodu elektrycznego i położeniem elektrod, ale również do sterowania wdmuchiwaniem węgla przy pienieniu żużla. Rozważając powyższe wymogi, ważnym jest wybór odpowiednich sygnałów pomiarowych. Pomiar tylko sygnałów elektrycznych nie jest dostateczny dla systemu sterowania. Dla właściwego sterowania elektrodami ważna jest także informacja o ich położeniu.

W celu zdobycia danych został zbudowany specjalny system. System złożony jest z przenośnego komputera, wyposażonego w kartę do gromadzenia danych, systemu wzmacniania ze wzmacniaczami różnicowymi, filtrów przeciwzakłóceniowych i obwodów próbkowania i podtrzymywania. Oprogramowanie systemu umożliwia obserwacje on-line mierzonych sygnałów i zapis danych na dysku twardym. Po informacji pomiarowej uzyskanej ze stanu jałowego, wykonywane są trzy dwufazowe i trójfazowe testy zwarcia w celu kompensacji algorytmu obliczeń parametrów obwodu i opisu rzeczywistej wartości napięć łuku. Pozycje elektrod obliczone są na podstawie zarejestrowanych prędkości. Następnie wszystkie dane są analizowane off-line, w celu określenia parametrów modelu łuku i zdefiniowania stanów systemu sterowania. W artykule przedstawiono niektóre interesujące zjawiska zaobserwowane w systemie sterowania piecem.

1. Introduction

Modern steelmaking electric arc furnaces (EAF) are mainly used for steel scrap melting. A tap-to tap time is one of most important indices of the effective work of the arc furnace. This index is depending on the maximal thermal power supplying the furnace directly. This power is enveloping the electric power of electrical power system and the thermal power coming from burning coal, the natural gas and partly of scrap. Batch of the furnace in the route of the steelmaking process is changing an aggregation state, the temperature and the chemical constitution. Taking above into attention the determining of the state variables using the on-line measurement of the steelmaking process is very difficult and it can be even impossible. Therefore all measurable signals containing the information facilitating conducting the process are very important. From here among others acoustic signals generated by the furnace, the temperature of water in the cooling system and temperature of outlet gasses were being used for controlling a steelmaking process [1].

Work of the EAF electric power system, especially in beginning of melting time is very unstable due

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to physical changes of the scrap. It causes very high changes of powers and high harmonic content of currents. Hence the furnace is viewed as unstable, nonlinear three-phase load. Guarantee of the furnace stable work is very important for technological reasons and for the furnace influence on power system. To improve the furnace effectivity and reduction of generated disturbances, knowledge of the furnace electric circuit parameters and parameters of arc discharge model are very important. The knowledge of those parameters makes possible working characteristic calculating and electrode positioning controller gain calculating. The knowledge may be also useful for working point of the furnace determining and determining of actual state of the melting process

However the measurement of electric signals is not easy in the power system of the arc furnace due to high temperature of furnace atmosphere, use of foam slag and arcs penetration in melted batch. Currents of the high power circuit are reaching to 100kA and are generating the strong magnetic field. Therefore currents are most often measured on the primary side of the furnace transformer. "An arc voltage" is being measured on clamps of the secondary side of the furnace transformer. Therefore this voltage is a sum of the voltage drop on the resistance of the high power conductor, voltage drops induced by high power conductors and the real arc voltage [2].

Working characteristics of arc furnace circuit changes during technological process time. It is related with changes of characteristics of arc discharge. For finding closest to real characteristics of the furnace circuit it is necessary to describe nonlinear arc discharge model parameters and measurement of values needed to the model parameters identification.

It is possible to get the certain information about the state of the furnace from characteristics of arc discharges. The shape and parameters of current-voltage characteristics are depending on the temperature and the density of the arcs surroundings. A measurement of real voltages of the arc is necessary in that purpose. Knowledge of electrode positions can also be used to determine arc lengths which are important to calculate arc model parameters.

In our work a special measurement system was developed, in which determining of arc discharge model parameters are possible. The main purpose of system design was to find parameters that can describe state of melting process and make possible choosing correct settings for arc position controllers. In the project the experience got from earlier developed furnace monitoring system were very useful [3]. That system makes possible the furnace circuit parameters measurement and working characteristic calculating.

2. Description of furnace installation

Steelmaking arc furnace is three-phase device supplied from high voltage power system through main and furnace transformers. Transformer tap changer installed on middle voltage part of circuit changes voltages of secondary side of furnace transformer. Secondary side of furnace transformer is connected with electrodes by high current buses. Between electrodes and steel scrap the electric arcs arise. It converts electrical energy to high temperature thermal energy of the arc plasma. The diagram of the furnace installation and electric circuit measurement devices is presented in figure 1.

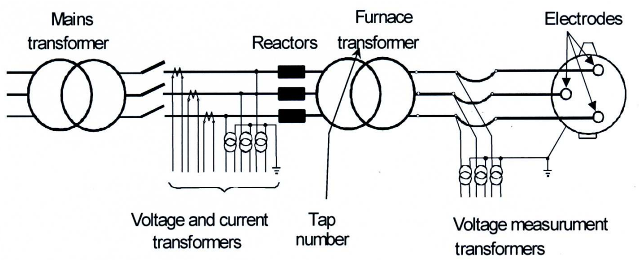

Fig. 1. Diagram of electric arc furnace installation [5]

The control tasks in furnace installation are performed by the choice of tap changer position and by electrode positioning controllers. They make possible to maintain of the furnace working point, set by the furnace supervisory control. Diagram of the arc furnace electrode positioning control system is presented in figure 2.

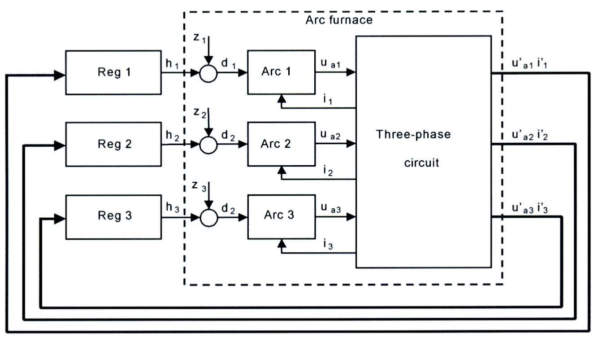

Fig. 2. Diagram of the arc furnace control system

Controllers installed in every circuit phase calculate regulation error using average or rms values of voltages and currents and then control the electrode positions. In the general form regulation error ε_k is calculated from equation (eq1)

$$\varepsilon_k = A \cdot U_k + B \cdot I_k + C, \tag{1}$$

where k= 1, 2, 3 – phase index.

Parameters A, B, C are defined by furnace working point, optimised according to the process technology and taking into account the furnace working characteristics. Most often the melting time is taken as control criterion. Depending on A, B, C parameters choice, three methods of regulation may be distinguished:

- voltage regulation,
- current regulation,
- voltage-current regulation.

Driving systems of electrode positioning controllers can be electro-mechanical or hydraulical drives, working independently in all phases. Transfer functions in every phase may be approximated as follows

$$G_W(s) = \frac{1}{s} \cdot \frac{k_r}{Ts^2 + 2\xi Ts + 1}, \tag{2}$$

where: k_r – gain, T – time constant, ξ- dumping factor.

Control of the arc furnace on the basis of equation (eq2) makes possible proper running of technological process. However in some cases it may not work properly. The arc discharge characteristics are non-linear and arc furnace circuit is three-phase circuit without neutral conductor. That is why couplings between phases currents exist. It causes that phase electrode regulators do not work independently [4]. In a result disturbance in one phase generate disturbance in neighbouring phases. Another problem with furnace electrode position control is tied with arc discharge characteristic variations during the process [4]. It makes necessary of the adaptation of regulator gain k_r.

3. Models and measurement algorithms

To find the arc furnace working characteristics it is necessary to know furnace electric circuit parameters. Knowledge of those parameters is also necessary for calculation of proper voltages by compensation of voltages inducted in arc voltage measure loop. Equivalent diagram of the electric installation of the arc furnace, transformed to secondary (high-current) side of the furnace transformer is presented in figure 3.

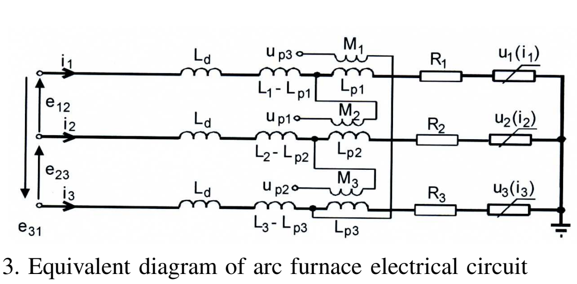

Fig. 3. Equivalent diagram of arc furnace electrical circuit

Taking into account the physical interpretation of inductance, spatial configuration of high-current buses and voltage measurement conductors an equivalent diagram of the arc furnace circuit consist of a high current circuit and a voltage measurement circuits. Identification experiment for the arc furnace electrical circuit parameters estimation is divided on three stages:

- measurement of supply voltages in no-load state,
- three two-phase short-circuit tests for reactances and resistances finding,
- three-phase short-circuit test for verification of founded circuit parameters.

The algorithm of parameters identification was described in [5] and used for modification of IEC 676 standard [6]. Voltages u_{pk} measured in a measuring circuits differ from real arc voltages u_k and are described by equation:

$$u_k(t) = u_{pk}(t) + R_k i_k(t) + L_{pk}\frac{di_k(t)}{dt} + M_k\frac{di_{mod(k)+1}(t)}{dt} \tag{3}$$

where: k = 1, 2, 3 – phase index.

For estimation of real arc voltages is necessary to know values of phase resistances R_k, measurement loop inductances L_{pk}, mutual inductances M_k and courses of derivatives of currents di_k/dt. Those parameters may be identified during three two-phase short-circuit tests. During the tests the equation (eq3) simplifies to form:

$$u_k(t) = u_{pk}(t) + R_k i_k(t) + L_{pk}\frac{di_k(t)}{dt}. \tag{4}$$

The derivatives of currents di_k/dt can be obtained by calculating from phase currents i_k. In the work five points Savitzky-Golay filter algorithm were used for filter data and calculate current derivatives. For data which were recorded during three two-phase short-circuit tests, parameters R_k and L_{pk} can be calculated from equations

$$R_k = \frac{\int_0^T u_{pk}(t) i_k(t)dt}{\int_0^T i_k^2(t)dt}, \quad L_{pk} = \frac{\int_0^T u_k(t)\frac{di_k(t)}{dt}dt}{\int_0^T \left(\frac{di_k(t)}{dt}\right)^2 dt}, \tag{5}$$

The mutual inductances M_k can be evaluated from differences between calculated inductances L_{pk} calculated for different two-phase short circuit tests [5].

To decrease influence of couplings between electrode position controllers and to find correct values of gains in control loop is necessary to know actual arc discharge characteristics. To solve this problem in real-time, model of arc discharge should be adequate and as simple as possible and its parameters should be easy to identify.

Between many models characteristics which may be found in literature. Especially useful is simply model of DC arc developed by Lowke [7] in the form

$$U = c \cdot I^a d^b, \tag{6}$$

where: d – arc length, a, b, c – arc model parameters.

The model describes that arc voltage have the same polarity as the current. Hence it may be adapted to describe AC arc discharge. Making some modification in that model is possible to get proper description of AC arc discharge with following equation [5]:

$$u(t) = c \cdot |i(t)|^a d^b sign(i(t)). \quad (7)$$

The parameters a, b, c depend on melting phase of the process. These parameters can be estimated using simply identification algorithms. Identification of the arc model parameters require measurement of real arc voltages $u(t)$, phase currents $i(t)$ and arcs length d. Because above parameters change during melting time, to describe parameter changes continuous data measurement for whole melting time is necessary. Main problem is impossibility of direct measurement of arc length. The value of arc length changes when the electrode moves, electrode burns and the scrap goes down.

For arc length changes estimations indirect measurement method was applied. The electrode speeds signals were integrated and with connection to some events may represent arc length.

4. Monitoring system architecture

Structure of measurement system is presented in figure 4. It consists of some layers performing different tasks. First layer is integral part of the furnace and consists of measurement transducers and signal dividers. It ensures required range of measurement system input signals.

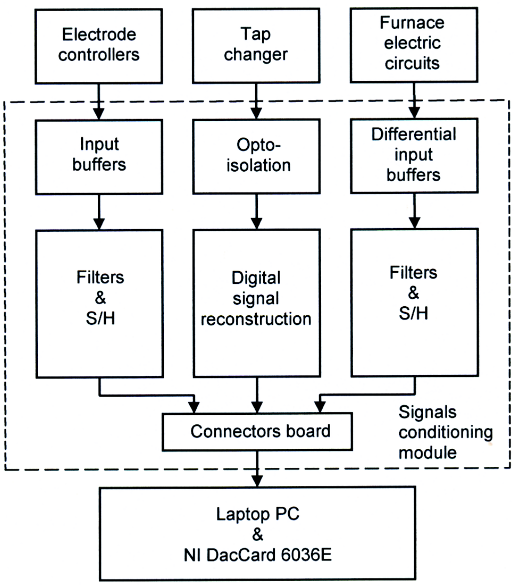

Fig. 4. Diagram of acquisition system

The layer is divided on:

- phase voltages measurement circuits connected in neighborhood of electrode grips,
- voltage transducers installed on furnace transformer primary side measure supply voltage of furnace,
- current transducers installed on furnace transformer primary side,
- electrode speed measurement circuit, isolation circuits and current loop driver,
- arc furnace transformer tap changer signals.

Signals from this layer are transferred to furnace control room where signals conditioning module is installed. The module consists of input blocks divided in functional sections:

- differential buffer amplifiers for acquisition signals of arc voltages, currents and supply voltage,
- current loop receivers of signals from electrode position drivers,
- opto-isolation module reading information from tab changer.

After signal processing in input blocks, voltage and current signals are filtered and latched in sample & hold buffers for simultaneously reading by data acquisition card. The electrode speed signals are processed in the same way. Signals from tap changer are reconstructed and converted to TTL level. Next all signals buses pass to next layer consist of laptop computer with data acquisition card NI-DAQ-Card 6036E from National Instruments. This card has 16 analog inputs, eight digital I/O and 2 analog outputs. Analog inputs are multiplexed and sampled with 10 kHz sampling frequency in all chanels.

5. System software

Software of designed system makes possible data acquisition from all channels for whole melt (about 60 minutes). Acquired data are stored on computer hard disk. Additionally application has added module for on-line visualization of measured data, voltage-current characteristic calculation, average or rms values calculation. and arc model parameters identification.

Software for data acquisition uses acquisition card drivers for Windows operating system provided by the card manufacturer. The drivers make possible the acquisition card configuration and data acquisition by calling function from DLL library from high level languages such as C, C++, VB, Python. In software development set of functions called in documentation Traditional NI-DAQ [8] have been used. These functions make possible double buffering data acquisition. This way of the card operating make possible long time data acquisition with high frequency, data visualization and data storing on hard disk without pauses in acquisition.

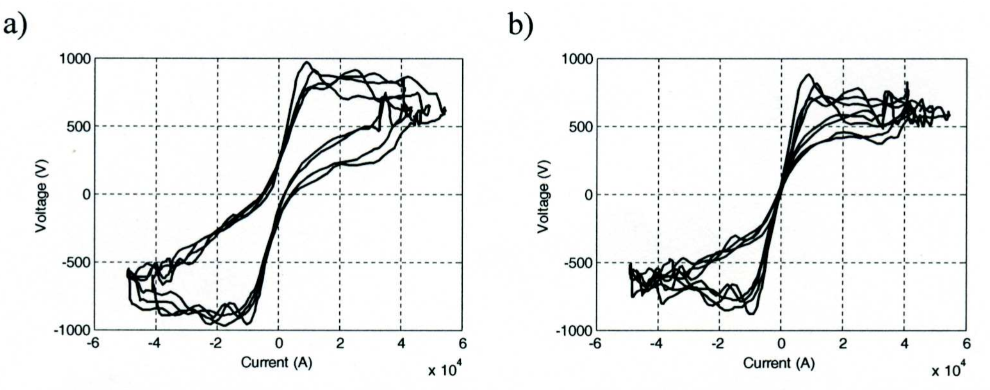

Fig. 5. Characteristics of arc voltages versus currents a) before compensation, b) after compensation of voltages generated in measurement loop

6. Measurement results

During data acquisition from an arc furnace, ten signals were acquired. There were three signals of arc voltages u_{pk}, three phase currents i_k, three speeds of electrode movements v_k and one supply voltage, measured on a primary side of the furnace transformer. The data were recorded during the are furnace working time with frequency of 10 kHz on every channel. For one melting process about 700MB of data were saved on a hard disc. Exemplary current-voltage characteristics before and after compensation are presented in figure 5a and 5b.

The plots show that using signals without compensation to control of the electrode movements may cause problems with maintaining the defined arc furnace working point.

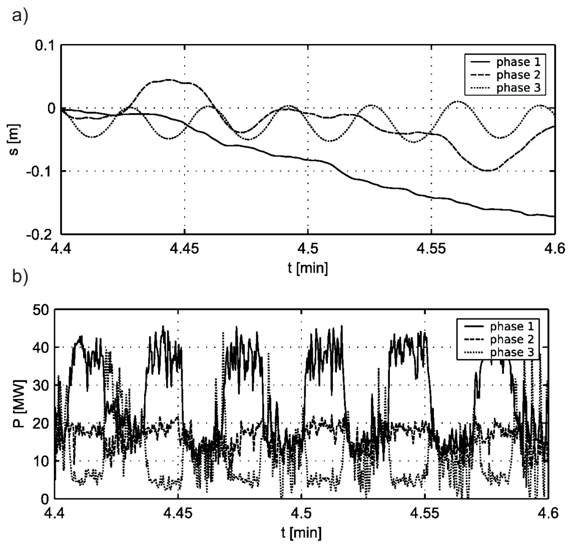

Fig. 6. Heavy piece of scrap under electrode of phase 3, a) electrode movements, b) arc active powers

Next plots show some interesting phenomena observed during process. The first of it shows the electrode positioning system when heavy piece of scrap lay under electrode of phase 3. It causes that the arc was cooled and very unstable. Hence melting of scrap were slower than under others electrodes.

Duration of this phenomenon was about 2 minutes. Figure 6a presents electrode movements in all phases. Oscillation in phase 3 causes very high changes of phase powers, which can be observed in figure 6b. It prolongs melting time and cause high disturbances in supply network.

Another observed phenomenon is presented in figure 7. These phenomena can be interpreted as sliding a scrap. At the beginning of phenomena the arc resistance changes between 4 and 12 mOhms and has decreasing trend. It can be caused by injection of coal powder to the furnace. In the result electrical parameters of arc environment are changing and also electric arc parameters. Decrease of arc resistance cause electrode movements. But these movements did not change arc parameters. So in consequence electrode movements cause break of the arc. This phenomenon cannot be properly interpreted basing on electrical signals. In control system without measurement of electrode positions counteracting the phenomenon is impossible. In the result the process time is also prolonged.

Other phenomenon was observed during electrode moving up at the end of melting the basket two and three. Recorded signals as a function of electrode movements are presented on figure 8. During electrode moving up the arcs do not disappear. Increase of current values may be observed on the figure 8b. If electrodes are at upper position the arc can damage the roof of the furnace. The high current is also dangerous to power supply switches. Turn-off the circuit with high value of currents makes the switch life shorter.

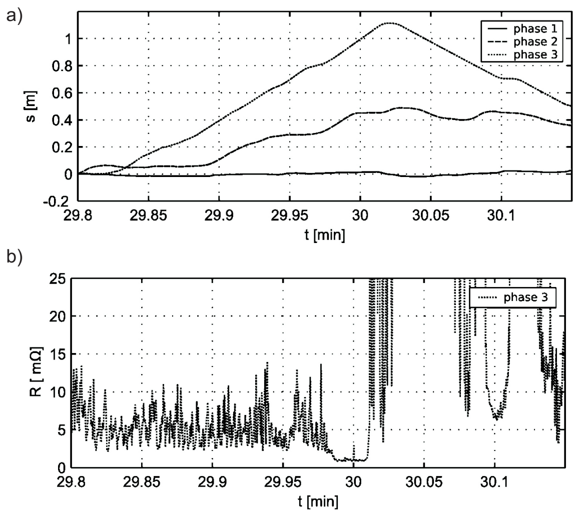

Fig. 7. Uncontrolled electrode movements: a) electrode movements, b) arc resistances

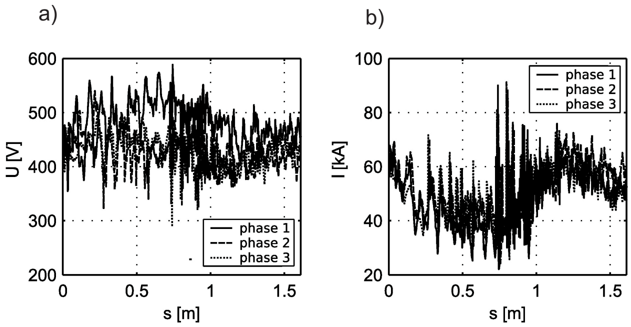

Fig. 8. Courses obtained during electrode lifting: a) arc voltages, b) currents

7. Final remarks

The calculation method of real arc voltage was worked out in the seventieth years of previous century [2]. But still it is very rarely applied. The contemporary technique of digital signals processing is facilitating the build of observers of arc voltage, outlining reactive and active powers, determining disturbances generated to the power network, outlining parameters of characteristics of the arc. Such algorithms were being applied off-line to analysis on the PC computer the data collected on the real arc furnace.

Analysis of recorded data permitted to observe irregular phenomena during the melting process. Explaining these phenomena without considering electrodes position is almost impossible. For outlining the arc voltage is necessary the knowledge of the resistance and inductances of measuring circuit. Worked out in [5] algorithms were tested for a few arc furnaces and were very useful in practice.

Proper control of electrodes of arc furnace only on the basis of electrical quantities is insufficient in real exploitation of arc furnace. To improve the furnace control system it is important to measure (estimate) electrode positions. This information is needed to determine irregular situation during the furnace operation which require a special control strategies. Application these strategies in control system of the arc furnace allows to improve the melting process effectivity , makes process conducting more reliable and let to decrease negative influence of the furnace on power system.

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Received: 3 April 2008.