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Some aspects of the analysis and the interpretation of electrical measurements of submerged arc-resistance furnace

***Abstract**. The article describes measurement of currents and voltages in submerged arc-resistance electric furnace which were done to identify arc parameters. Waveforms of registered currents and voltages have been shown. Characteristics of arc developed in original C# software have been presented.*

***Streszczenie**. Artykuł opisuje pomiary prądów i napięć w obwodzie pieca elektrycznego łukowo-oporowego z łukiem krytym, które zostały wykonane w celu identyfikacji parametrów łuku. Zaprezentowano przebiegi zarejestrowanych prądów i napięć. Przedstawiona charakterystyka łuku została wyznaczona za pomocą własnego programu napisanego w języku C#. (**Pewne aspekty analizy i interpretacji pomiarów wielkości elektrycznych pieca łukowo-oporowego**).*

Keywords: submerged arc-resistance furnace, electric arc, nonlinear systems, electrical measurements.
Słowa kluczowe: piec łukowo-oporowy, łuk elektryczny, układy nieliniowe, pomiary wielkości elektrycznych.

Introduction

Ferrosilicon is one of the basic raw materials in the steel industry. It is an alloy of iron and silicon. The production of the ferrosilicon in submerged arc-resistance electric furnaces has steadily expanded during the past decades. It is associated with a high technological demand for ferrosilicon which is used as a source of silicon to deoxidize steel and other ferrous alloys. Ferrosilicon is also used for manufacture transformer and electric motors cores. The power consumption during the production of ferrosilicon is very high, so the reduction of power looses is very desirable in this process. It can be done by appropriate control of the entire process, but it requires a great knowledge about raw materials, process and its thermal and electrical parameters [1].

The article deals to the identification of some electrical parameters which are important for the control of thermal process. An exemplary schematic diagram of a submerged arc- resistance electric furnace with measured currents and voltages has been shown in fig. 1.

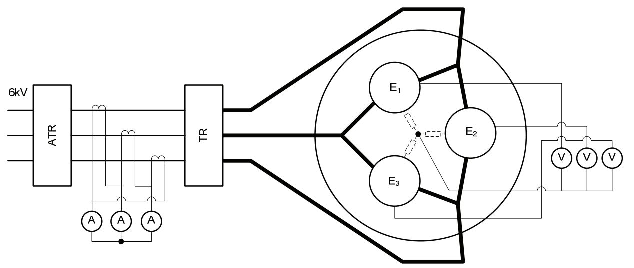


Fig.1. A schematic diagram of a submerged arc furnace with simplified measured systems

The uncontrolled nature of the steel melting process is a source of the unpredictable and random currents and voltages harmonics generated by arc furnace [2, 3]. As a result of these permanent fluctuations of currents, voltages and powers, the electric energy is introduced into the furnace in an inhomogeneous manner. This conclusion makes difficult the control process of the arc furnace. The control system based on maintaining constant current or constant impedance is very often used.

There are three sources of control for the furnace:

- by the control of the raw material,
- by the moving of electrodes,
- by stepping up or down the electrode voltage.

Unfortunately, neither maintaining a constant current nor a constant impedance do not provide an optimal supply conditions and a production.

The dynamic and extensive measurements on the furnace have been developed. The results of these measurements have been presented in this article.

Description and analysis measurements

The submerged arc-resistance furnace in the company Re Alloys (Łaziska Górne, Poland) has been used to produce ferrosilicon FeSi75. It is powered from factory power system 6kV by means of 12MVA autotransformer. The transformer of the furnace gives voltage range from 70 to 140V. This system of transformers is connected to electrodes by the high current busduct. The current in electrode is about 35kA and the total power consumption is equals of 8,5MVA with tgφ≈0,48. The simplified diagram of the system has been shown in fig. 2.

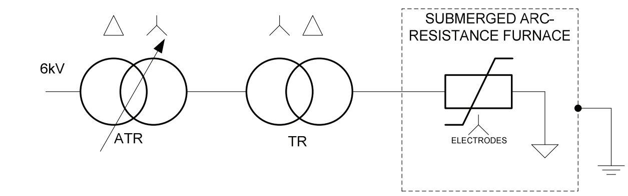


Fig.2. Simplified diagram of considered arc furnace

In the considered and metered object the high current busduct is bifilar. It was designed according to the paten application No P-396034 and its construction makes possible symmetrical work without dead phase effect [4], what means uniform distribution of power density under electrodes. Registered states of transition from the asymmetrical state to the symmetrical state are long in time processes, which the control requires adequate knowledge of the operator. Accordingly processed measurements should develop operator awareness and be helpful in the optimal process control.

Suitable equipments have been used for measurements. Phase voltages of electric arc furnace have been measured directly on the columns of electrodes in the measurement system. The voltage of an electrode is collected from its coat derived over the cap of the furnace (Fig. 1) and it is referenced to the anti-electrode which is placed in the bottom of the tank furnace. There is a conventional zero point. The currents flowing by electrodes have been determined from measurements currents by means of current transformers (Fig. 1) connected in the primary side of the furnace transformer. Collected a large number of measurements allow observing the state of the transition of the furnace from asymmetry to symmetry.

Recorded waveforms of voltages and currents of the arc allow plotting characteristics of the arc in a dynamical way. This characteristic has been determined based on the well-known Cassie model [5, 6]:

(1) $$\frac{di(t)}{dt} = \left[e_k(t) - R_{ek} i(t) - \frac{i_k(t)}{g_k(t)} \right] \frac{1}{L_k},$$

(2) $$\frac{dg_k(t)}{dt} = \frac{g_k(t)}{\Theta_k} \left[\frac{i_k^2(t)}{g_k^2(t) U_{\tau k}^2} - 1 \right],$$

where:

k=1, 2, 3; $U_{\tau k}^2 = \frac{1}{T} \int_{t_0}^{t_0+T} u_{\tau k}^2(t) dt$; $\sum_{k=1}^{3} i_k(t) = 0$;

$i_k(t)$ – measured current of k phase; $e_k(t)$ – measured k - electrode voltage; R_{ek} – substitute resistance of k - electrode; $g_k(t)$ – electric arc conductance; Θ_k – time constant of electric arc.

The reactance of the high current busduct has determines by means of known method [7] in the moments of the current crossing through zero. Sampled current waveforms have emphasized quantization effect. In order to increase the zero detection accuracy the sampled current waveforms have been subjected to the FFT analysis. The calculated Fourier coefficients are used to determine the analytical form of the current waveform. The moments of the current crossing through zero have been detected on current waveforms determined in this way. The voltage and current waveforms, distorted through the nonlinear nature of the electric arc have been shown in Fig. 3 and 4. Exemplary results of registered waveforms FFT analysis have been shown in Fig. 5.

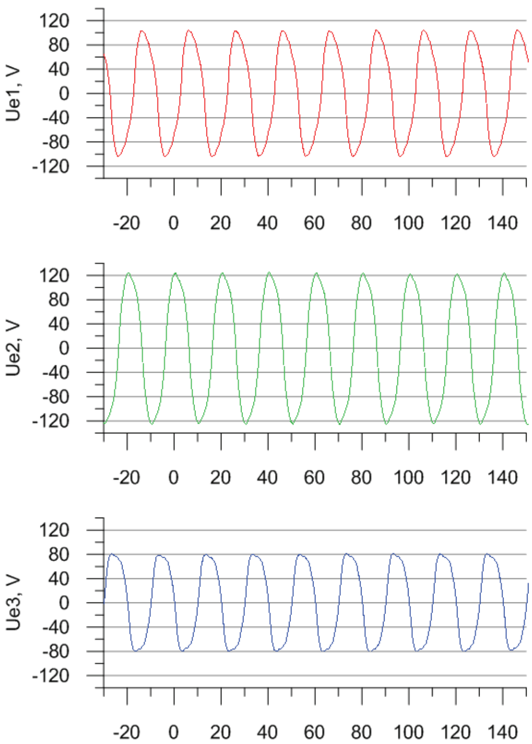


Fig.3. Asymmetric state of the furnace operation – the waveforms of voltages of electrodes

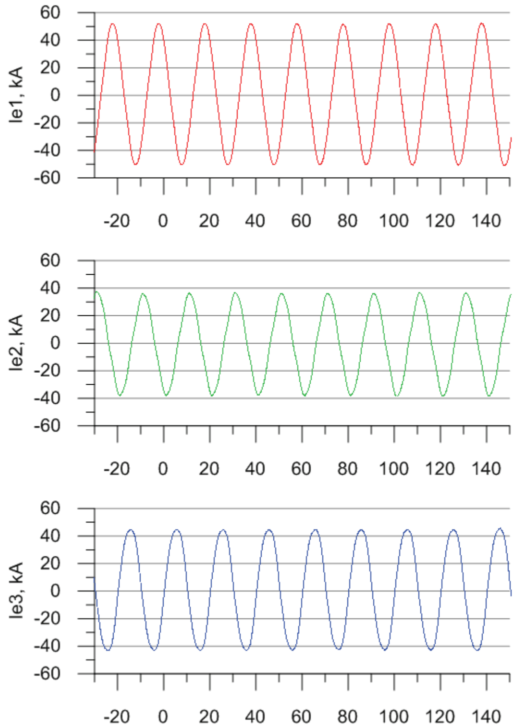
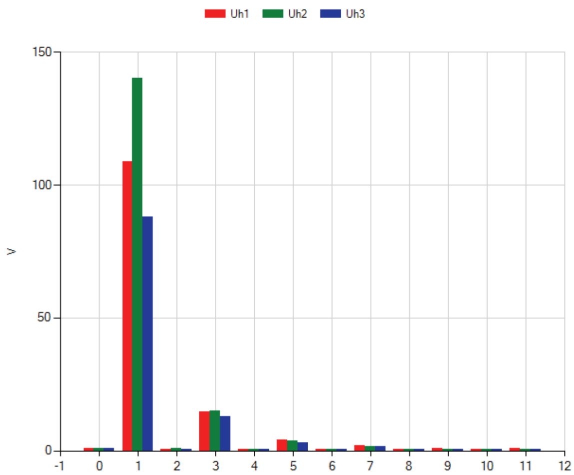


Fig.4. Asymmetric state of the furnace operation – the waveforms of currents flowing by electrodes

a)



b)

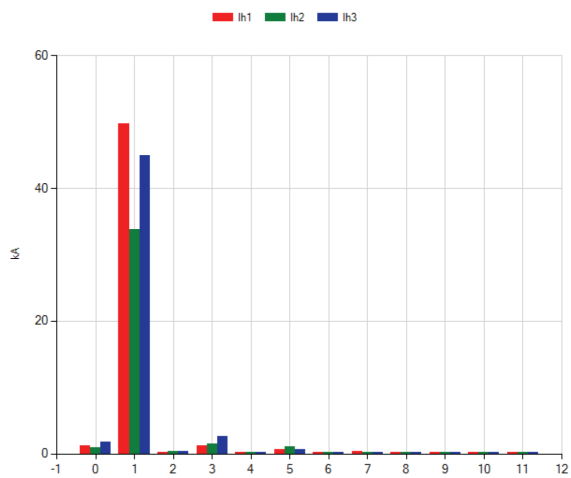


Fig.5. FFT analysis of the measured a) voltages of electrodes and b) currents following by electrodes

In considered cause of the submerged arc-resistance furnace, the inductance of the high current busduct is very large. This large inductance makes only the fundamental harmonic dominates in the current spectrum, as shown in Fig. 5b. Assumption of the sinusoidal current makes possible transform of the equation (1) into the form (3):

$$\text{(3)} \qquad \frac{du}{dt}(t) = \left(\frac{1}{\Theta} + \omega \cot(\omega t)\right) u(t) - \frac{1}{U_{\tau k}^2} u^3(t) \,.$$

The equation (3) is known form of the Bernoulli differential equation. This equation gives the solution in the following formula [8]:

$$\text{(4)} \qquad u(t) = \frac{2U_{\tau k}^2 \sin(\omega t)}{\sqrt{2\Theta\left(1 - \frac{\sin\left(2\omega t + \arctan\frac{1}{2\omega\Theta}\right)}{1+(2\omega\Theta)^2}\right)}} \,.$$

In this case, it can be avoid a large number of FFT operations and it can be written the voltage waveform and its coefficients of the Fourier series in closed form [9, 10]:

$$\text{(5)} \qquad U_h = \sqrt{A_h{}^2 + B_h{}^2}\, \sin(h\omega t + \varphi_h) \,,$$

where:

$$\text{(6)} \qquad A_h = \frac{1}{2\pi}\int_0^{\frac{2\pi}{\omega}} u(t)\cos(h\omega t)dt \,,$$

$$\text{(7)} \qquad B_h = \frac{1}{2\pi}\int_0^{\frac{2\pi}{\omega}} u(t)\sin(h\omega t)dt \,,$$

$$\text{(8)} \qquad \varphi_h = \arctan\left(\frac{B_h}{A_h}\right).$$

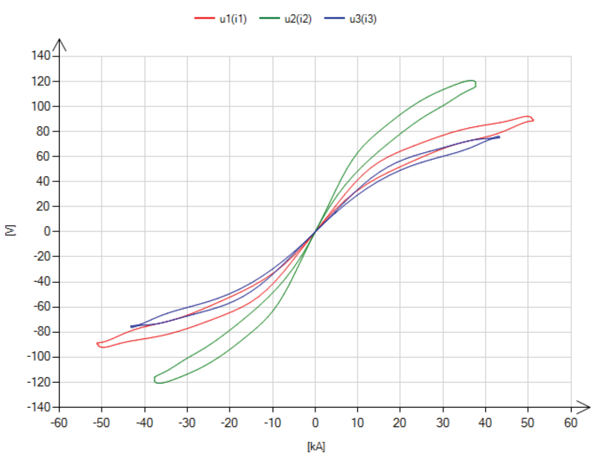


Fig. 6 The hysteresis curves of the electric arc for each phase.

The dynamical state of the electric arc burning under each electrode is shown in Fig. 6 in form of hysteresis curves. Based on the recorded waveforms, an identification of other parameters of the arc and the high current busduct have been done using specifically for this purpose software written in C#.

Recorded waveforms are consistent with the waveforms recorded in the plant measurement system of the furnace. Confirmed operating states (asymmetric and symmetric) are discernible in the waveforms of voltages and currents.

Conclusion

Identification of the parameters of the arc has been done for each period of the waveforms of the arc current and voltage. Derivatives of the currents of electrodes needed to identify the parameters of the arc have been determined after an application of elementary methods of signal processing. However, it seems that application of Rogowski coils would be better and it would better identify the parameters of the arc furnace. Identification of the parameters of the arc can be makes by means of the contemporary real-time control systems. It is possible in this case, if the number of DSP operations will be reduce so that the algorithm was executed in one cycle.

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