Study About the Possibility of Electrodes Motion Control in the EAF Based on Adaptive Impedance Control

CONFERENCE PAPER · OCTOBER 2008

DOI: 10.1109/EPEPEMC.2008.4635465 · Source: IEEE Xplore

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Study About the Possibility of Electrodes Motion Control in the EAF Based on Adaptive Impedance Control

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***Abstract*—The paper presents a study about the possibility of adaptive process control in three phased electric arc furnace. The method is based on the electrodes motion control. The control principle is depending on impedance of the electric arc. The method proposed use a data acquisition board whose input signals are taken from electric arc. These signals allow the calculation of electric arc impedance. Using a numeric computer, it can be commands the control of electrodes position independently on each one of three phases. We propose to use a static frequency converter on each phase to control the electrodes motion**

***Keywords*— Adaptive control, motion control, power factor correction.**

I. INTRODUCTION

An electrical arc furnace (EAF) changes the electrical power into thermal energy by electric arc in melting the raw materials in the furnace. During the arc furnace operation, the random property of arc melting process and the control system are the main reasons of the electrical and thermal dynamics. That will cause serious power quality problems to the supply system [1], [2], [3], [4], [5], [6], [7].

Nowadays, AC-Electric Arc Furnaces (EAF) is typically designed to melt a batch of scrap into liquid metal within 1-3 hours [8]. Therefore the installed power reaches up to 1 MW/t. Melting down the scrap bunch and superheating it is a high dynamic process. The AC arc furnace has a non-linear current-voltage characteristic. Therefore it acts as a source of disturbance in the grid from which it is supplied. It emits both harmonics and interharmonics and generates voltage unbalances, voltage dips and voltage fluctuations. Another disadvantage in the EAF is caused by the variations in the line voltage leading to flicker, which can be observed due to the luminosity fluctuation of incandescent lamps.

However, one of the most substantial disadvantages of arc furnace is caused by the reactive power due to the non-linearity of the electric arc [9], [10]. The significant values of the reactive power cause important losses of active power, therefore the efficiency are affected [1], [2], [5], [6], and [11].

The closed-up loop control is not optimized at many furnaces; the run of voltage is very dynamic. With a more optimized control closed-loop it should be possible to enhance the energy input and consequently the productivity. For improving the functioning regime by power factor correction it is possible to make an adaptive impedance control.

The proposed solution is based on some measurements made on an industrial Plant in Romania, Hunedoara where a 100t, 100 MVA UHP EAF are in function.

II. THE ELECTRICAL PARAMETERS OF THE EAF

Figure 1 shows the physical model of the electric arc furnace [8]. In this particular EAF model, there are three electrodes that are moved vertically up and down with hydraulic actuators. Each of these electrodes has a diameter of roughly 1.5 m, weighs approximately 40 tons and is 1 to 2 stories tall. The ore is melted with a huge power surge from the electrodes. The actual product is denser than the scrap and thus falls to the bottom of the furnace creating the matte. Above the matte lies the slag where the electrode tips are dipped. The tremendous heat created by these electrodes causes the ore to liquefy and separate. Thereupon more raw materials are placed in the furnace and the process repeats itself.

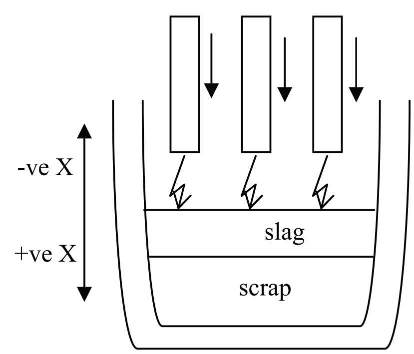

Fig. 1 The physical model of the Electric Arc Furnace

A. Arcing

Arcing is a phenomenon that occurs when the electrodes are moved above the slag. As the electrode approaches the slag, current begins to jump from the electrode to the slag, creating electric arcs. Depending on the magnitude of the input voltages of electrodes, the arcing distance can vary. Usually, arcing occurs in the region within centimeters of the slag (approximately 10 – 15 cm). Therefore, the EAF model must take into account the instances when x1, x2, x3 are negative (i.e. the electrodes are suspended above the slag), like in fig 1.

B. Characteristics of the AC electric arc

As given in [1], [9], [10], [11], [12], [13], one can consider that during the burning of the AC electric arc, the equivalent diagram of the supplying circuit can be represented as shown in figure 2.

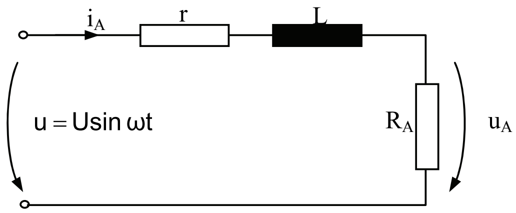

Fig. 2 The equivalent scheme of the supplying circuit of the AC electric arc

The variation curves of the electrical issues from the equivalent scheme of the supplying circuit are presented in figure 3. Analyzing the variation curves, we obtained the following conclusions: after electric arc ignition, the arc voltage u_A is practically constant and because the current is variable, the electric arc can be considered as a non-linear receiver; the arc voltage u_A and the current i_A from the circuit are in the same phase, which means that the electric arc has a resistive character; the electric current in the circuit passes through zero twice, in each period of the alternating voltage applied, which leads to the going out and re-ignition of the arc with a frequency that is double as compared to the voltage applied; the ignition voltage U_{ig} of the electric arc is higher than the work value U_A; the AC electric arc has a rectifying character [9], [10], [12]. That mean if there is a discharge between an electrode (usually made of graphite) and the metal to be heated up, due to the different thermal - physical properties of the two materials, (the temperature of the graphite electrode is higher than that of the material to be processed), the arc ignition voltage in the half-period where the metal represents the cathode is higher than the arc ignition voltage in the half-period when the cathode represents the graphite electrode, i.e. $U_{ig}^{+} >|U_{ig}^{-}|$. Similarly, for the drop voltage in the two half-periods, relation $U_d^{+} >|U_d^{-}|$ stands. For this reason, the amplitude of the current in the two half-periods differs, namely it is higher in the half-period when the graphite electrode is the cathode.

In figure 4 is show the dynamic characteristic of the AC electric arc, characteristic obtained according to the variation curves of $u_A(t)$ and $i_A(t)$ given in figure 3. The rectifying character of the electric arc is present because the magnitude of the ignition and drop voltage is different in the two half-periods. The burning of the electric arc can take place under the conditions of interrupted current or uninterrupted current. The burning under conditions of interrupted current leads to its unstable working and the current curve is highly distorted. For this reason it is necessary for the electric arc to burn uninterruptedly. The condition of uninterrupted burning of the arc, under the simplifying hypotheses that $U_{ig}^{+} \cong \left|U_{ig}^{-}\right| \cong U_{th}^{+} \cong \left|U_{th}^{-}\right| \cong U_A$ and the feeding voltage is sinusoidal $u_s(t) = U_s \cdot \sin\omega t$ is given by

$$U_s \cdot \sin\varphi \geq U_A . \quad (1)$$

this leads to

$$\frac{U_A}{U_s} \leq \sqrt{\frac{1}{1+\frac{\pi^2}{4}}} = 0{,}54 \quad (2)$$

resulting that in order to have an uninterrupted current, the electrical installation must work under a natural power factor

$$\cos\varphi \leq 0{,}85 \quad (3)$$

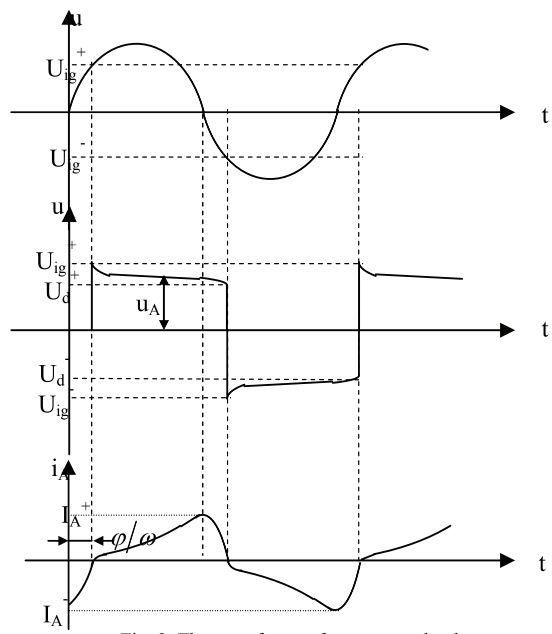

Fig. 3. The waveforms of currents and voltages

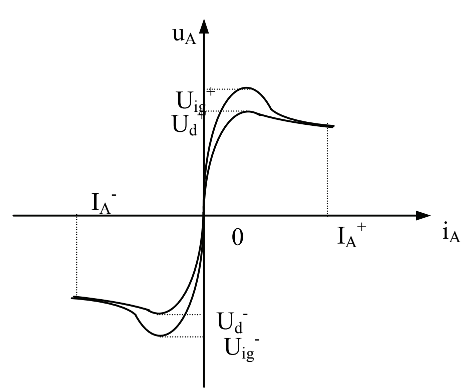

Fig. 4. The dynamic characteristic of the AC electric arc

III. MEASUREMENTS MADE ON THE EAF

The measurements were made at a 3-phase power supply installation of a 3-phase EAF of 100 t, to which were not connected the filters for the current harmonics, neither the load balancing device nor reactive power compensation. The modern methods of measuring the electric values are using numerical systems, based on data acquisition systems, and method presented in this paper are using such a system. It's been used a computer system with an ADA3100 data acquisition board. The measure scheme is show in fig. 5. The main characteristics of the ADA 3100 acquisition board are:

- 8 differential analog channels or 16 channels between ground and input
- 16 bits analog to digital conversion
- Inputs between ±5V; ± 10V
- 1, 2, 4, 8 an 16 programmable gain
- 8 ko FIFO memory
- 8 numerical inputs and 8 numerical outputs
- 2 analogical output channels with 12 bits resolution
- Outputs voltages ±5V; ± 10V, 0 – 5 V, 0 – 10 V

The acquisition board allows the simultaneous acquisition of 3 currents and 3 voltages, for the low or medium voltage lines of the transformer which supplies the furnace. The data acquisition on the 6 channels was made as follows:

- during 250 ms have been acquired simultaneously the data on the 6 channels, the selected acquisition frequency being of 5 KHz. In this way, have been acquired the signals during 12,5 periods. This fact allowed that in case the frequency of the supply voltage is different of 50 Hz, the data should contain a number of 12 full periods, selectable by program;
- the data acquisition memory the previously acquired data. In this way, results that have been acquired, on the entire duration of the heat, data in time windows of 250 ms length, the interval between two consecutive data windows being of 10 seconds.

The process was restarted, during 250 ms, at an interval of 9,75 seconds, interval during which were saved in memory the previously acquired data. In this way, results that have been acquired, on the entire duration of the heat, data in time windows of 250 ms length, the interval between two consecutive data windows being of 10 seconds. As regards to the waveforms of the currents and voltages on the low voltage supply line, presented in fig. 6, is found a strong distortion of these. Also, one can notice that because the amplitudes of the currents and voltages on the 3 phases are unequal, results that the load is also unbalanced.

The spectral characteristics of the current and voltage were achieved by using a Matlab program by processing the data acquired by using the Fourier rapid transform, and are show in fig. 7. One can observe the presence of harmonics of 3th, 5th, 7th order, but also the components of other frequencies than the harmonics' (inter-harmonics).

For the comparison of the simulation results and the performed measurement it was made simulations of the entire electric installation of the UHP electric arc furnace. The results of these simulations are detailed in several previous papers [2], [9], [10], [11], [12], [13].

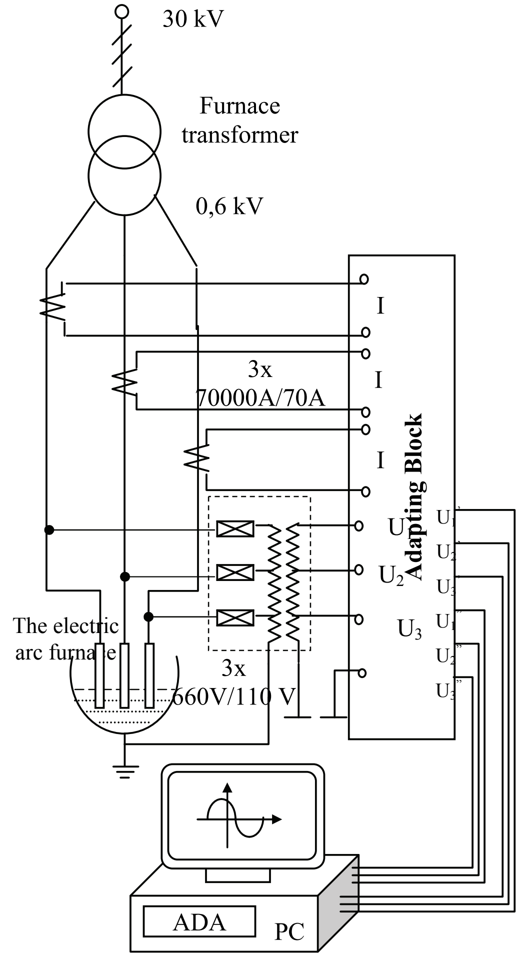

Fig. 5. The measure scheme

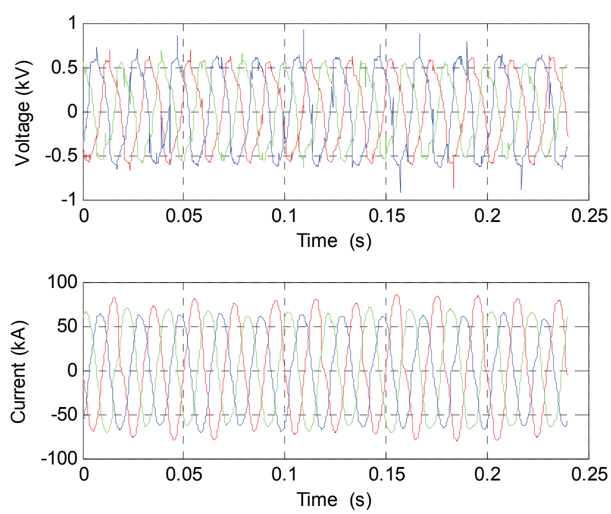

Fig. 6. The variation of measured voltages and currents for the three phases

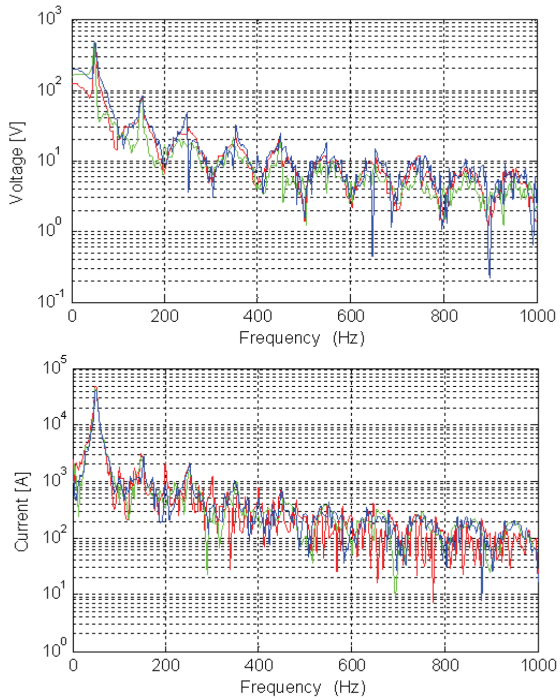

Fig. 7. The spectral characteristic of currents and voltages for measured data

It was calculate the main indicators of power quality and show in the table 1. These indicators are:

a) The active power absorbed is the mean over a period of the instantaneous power it absorbs:

$$P = \frac{1}{T}\int_0^T p \cdot dt = \frac{1}{T}\int_0^T u \cdot i \cdot dt \tag{4}$$

$$P = U_0 \cdot I_0 + \sum_{k=1}^{\infty} U_k \cdot I_k \cdot \cos\varphi_k \tag{5}$$

b) The reactive power absorbed by a dipole under non-sinusoidal work conditions is equal to the sum of the reactive powers corresponding to the harmonics:

$$Q = \sum_{k=1}^{\infty} U_k \cdot I_k \cdot \sin\varphi_k \tag{6}$$

c) The total harmonic distortion, is defined taking into consideration the first *40* harmonics

$$THD = \sqrt{\sum_{k=2}^{40}\left(\frac{F_k}{F_1}\right)^2} \cdot 100\,[\%] \tag{7}$$

d) The deforming power, specific to the non-sinusoidal, periodical work conditions, is defined by relation:

$$D^2 = S^2 - P^2 - Q^2 , \tag{8}$$

and has the expression:

$$D = \sqrt{\sum_{j>k}^{\infty}\sum_{k=1}^{\infty}\left[U_j^2 \cdot I_k^2 + U_k^2 \cdot I_j^2 - 2U_j U_k I_j I_k \cdot \cos(\varphi_j - \varphi_k)\right]} \tag{9}$$

e) The power factor under non-sinusoidal work conditions as ratio between the active and apparent power

$$k_P = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} \tag{10}$$

TABLE I.

	Measure values	Simulating values
P (MW)	48,52	47,36
Q (MVAR)	52,29	55,97
D (MVAD)	11.07	9.85
THDI (%)	10,83	8,44
THDU (%)	17,3	15,17
k_p	0.72	0.75

The powers variation for 6 minutes are show in figure 8. The powers was calculated using relations (4)-(9).

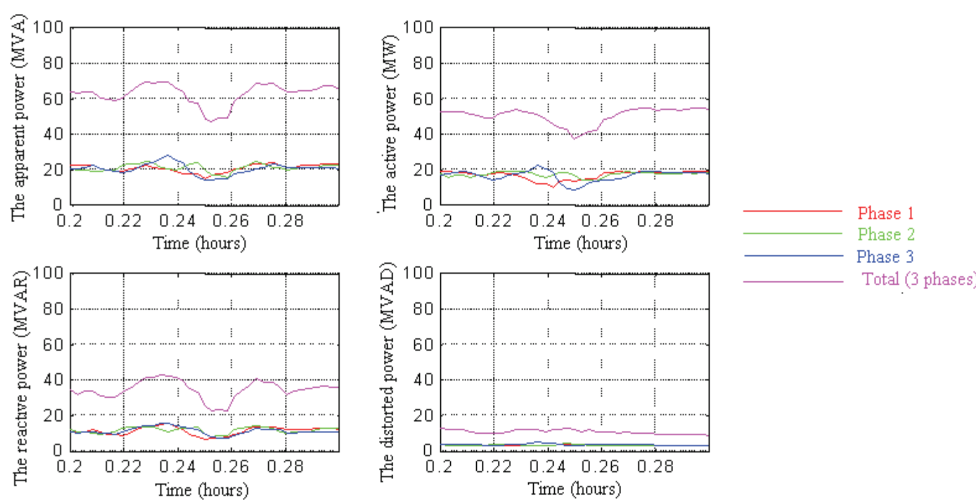

Fig. 8. Variation of powers for 6 minutes from the melting stage

IV. Development a Closed-up Impedance Control

The reactive power has high values, so the active power has to be control in the way that the reactive power will be reduced to minimal value.

The method is based on impedance adjustment. The electrode adjustment system has to be designed so:

$$Z = \frac{U}{I} = const \tag{11}$$

The impedance control is usual in the most of actual systems. The general control diagram is presented in figure 9.

The received dates from the electric arc furnace are transmitted to an interface block computer- frequency static converter. At the numeric output of the data acquisition board is transmitted a byte whose 6 less significant bits determine the senses of frequency static converters. The static frequency converters (SFC) are used to control the asynchrony electric drives with powers between 0.2… 280 kW to obtain maximum efficiency and without reactive power consumption. In the control scheme from fig. 9 we propose to use SFC having the main characteristics:

- the output voltage (50 Hz) 3x380 V or 3x220 V
- the output frequency: adjustable between 0.1…600 Hz
- acceleration/breaking time: 0.1… 300s
- the possibility to memorize 8 fixed speed steps
- the possibility to choice the rotation direction
- the possibility to communicate with a PC

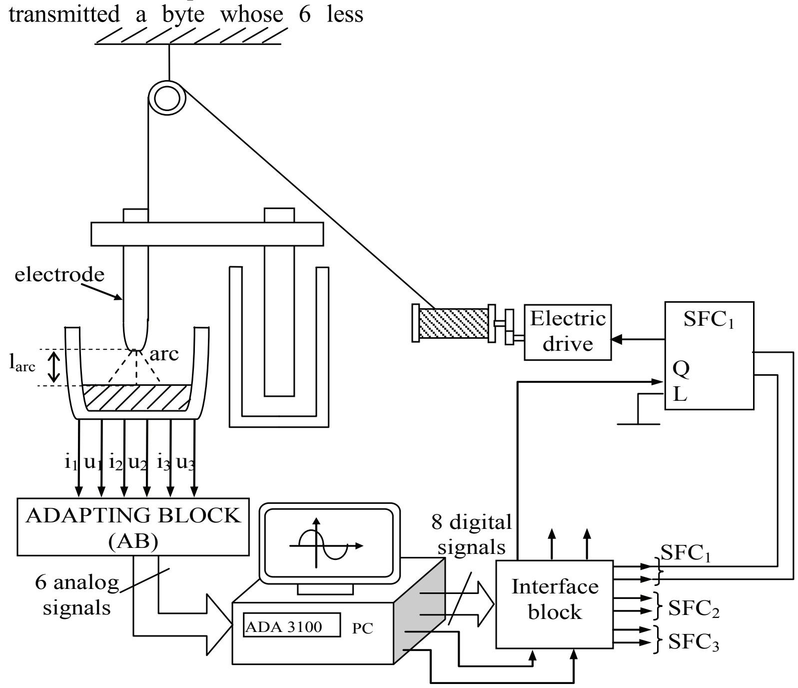

Fig. 9. The general control diagram

From interface block, every frequency static converter uses three outputs: one for control the electric drive speed and the other two for rotation command: in up and down sense of electrodes. Every frequency static converter involves an electrode through a reducer. Each frequency static converter controls an electrode using a reductor.

The proposed system functioning is based on an algorithm that is presented in figure 10.

The proposed method has the advantage allows the on-line determination of the electric arc impedance. The estimated errors are low because of the resolution of the analog-numeric converter.

$$\varepsilon_r[\%] = \frac{1}{2^{12}} \cdot 100 \approx 0.025\% \tag{12}$$

Another advantage of the proposed method is because of using frequency static converters that allows the elimination electromagnetic coupling used at control of electric drive – reductor movement. This electromagnetic coupling makes a heavy maintenance because of reduced reliability. Using the adequate command (through computer program) can be obtained the speed control from minimal to maximal value in 256 steps that is matching to an impose speed error of:

$$\varepsilon_r[\%] = \frac{1}{2^{8}} \cdot 100 \approx 0.4\% \tag{13}$$

The reliability of the frequency static converters is eliminating the necessity of using supplementary protection diagrams at increasing the nominal values of currents and voltages.

V. Simulation Results on Modifying the Electrodes Position

The simulations was made using PSCAD EMTDC, based on an electric arc model [9], [10], [11]. This model assumes the current – voltage characteristic of the electric arc described by the relation:

$$U_A = U_{th} + \frac{C}{D + I_A}\,. \qquad (14)$$

$$U_{th} = A + Bl\,. \qquad (15)$$

The electrical items variation in different functioning regimes can be done only if we consider an arc length variation between 0, corresponding to the short-circuit regime, and a maximum value. The maximum value is determined in such a way that the electric arc is burning.

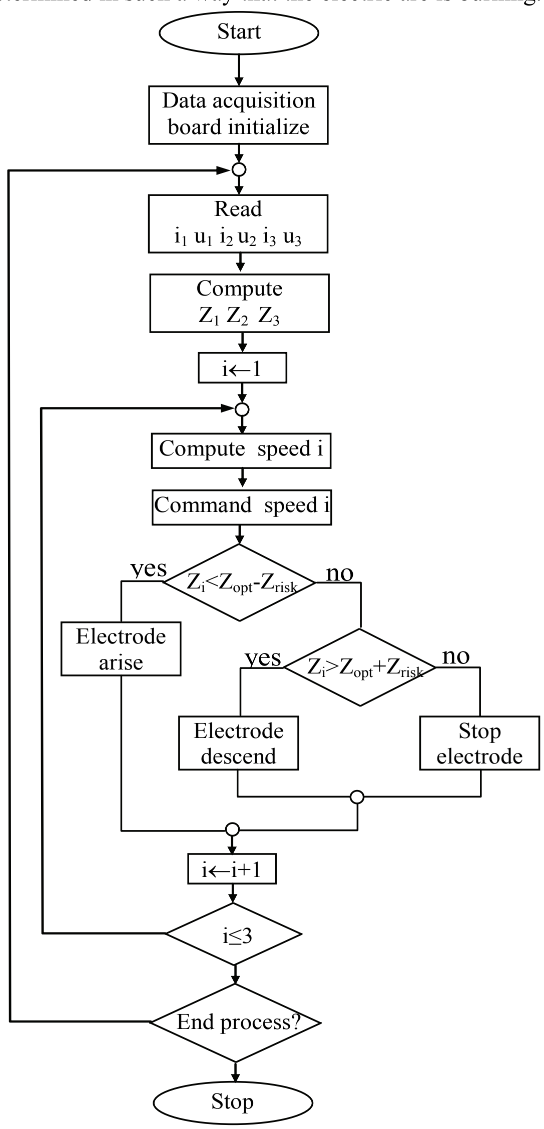

Fig. 10 The control algorithm

The electrodes position controlling is performed taking into account on the real condition existing on the considered industrial plant. The maximum motion speed of the electrodes is of *3 m/min (0.05 m/s)* and is reached in emergency regime, its variation being achieved as in fig. 11**.**

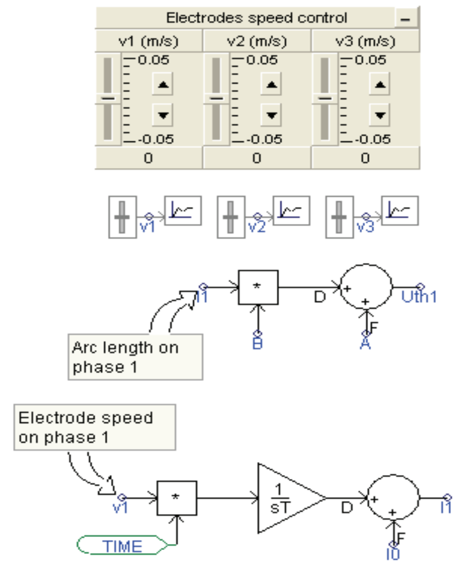

Fig. 11. The calculus of the arc length based on the electrodes speed

The electric arc's length can be modified from zero to a maximum value determined by limiting the integrator's output, fig. 11**;** The calculation of the drop voltage is made based on the relation (11)**,** the implementation diagram being also in fig. 11**;** The control of the electrodes' position is made independently on each phase.

The simulation results are presented in fig. 12. One can observe that the highest value of the active power is obtained when the value of the threshold voltage is of *200 V****;*** The reactive power is positive regardless the working regime, having values between *15-100 MVAR*, being therefore necessary the utilization of the reactive power's compensation installation.

In [11] was design the reactive power compensation system and harmonics filters. This contains the 4 filters on the harmonics 5, 7, 11 and 13 and the reactive power compensation installation composed by the constant part (in Y connection) and the adjustable part in steps. Since the threshold voltage depends linearly by the electric arc's length, it results that also the active power depends on the electric arc's length. Based on these remarks, the active power's iterative control algorithm proposed by the de authors is based on the modification of the electric arc's length depending on the active power desired to be obtained. In fig. 13 are show the results of active power control simulation following the reactive power's compensation and harmonics current filter.

CONCLUSIONS

The paper presents an adaptive control method of the electrode motion control at electric arc furnace by using a numeric system that have many advantages in the field of system reliability, working speed and estimated errors. By using such a method it is possible to correct also the power factor.

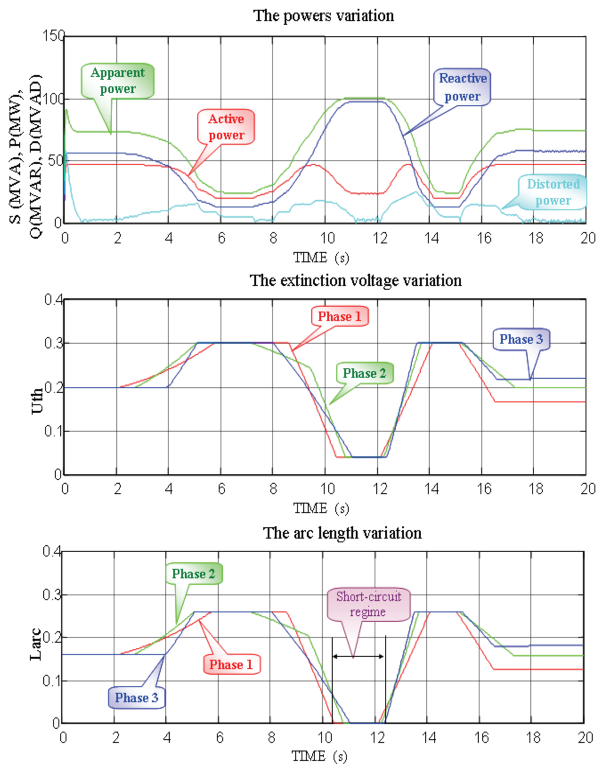

Fig. 12. The time variation of the powers, the threshold voltage and the arc lengths

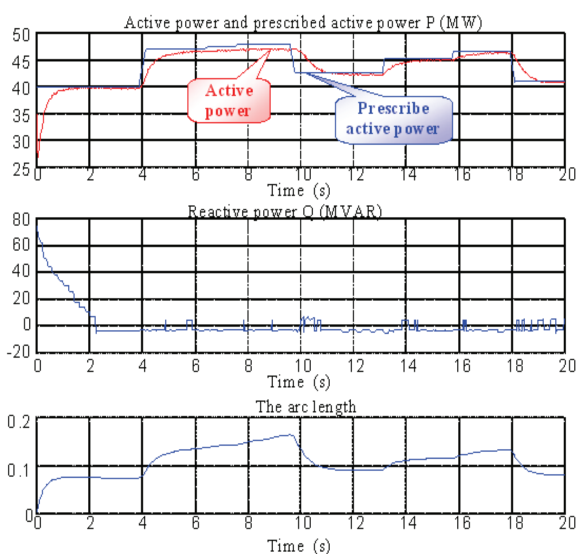

Fig. 13. The variation of active and reactive power and for the arc length obtained by simulation

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