ANNALS of Faculty Engineering Hunedoara
– International Journal of Engineering
Tome XIII [2015] – Fascicule 4 [November]
ISSN: 1584-2673 [CD-Rom; online]
a free-access multidisciplinary publication of the Faculty of Engineering Hunedoara

[1.] Loredana GHIORMEZ, [2.] Manuela PĂNOIU

CURRENT CONTROL OF A 3-PHASE ELECTRIC ARC FURNACE USING FUZZY LOGIC

[1.] University Politehnica Timisoara, Faculty of Automation and Computers, Timisoara, ROMANIA
[2.] University Politehnica Timisoara, Faculty of Engineering Hunedoara, Hunedoara, ROMANIA

Abstract: This paper presents a current control for a three-phase electric arc furnace of direct action. In order to do this, a fuzzy control system is proposed. The fuzzy system is a Mamdani fuzzy model and the environment used is Matlab. It has the current deviations as inputs and electrode speeds as outputs. Modifying the position of the electrodes, different arc lengths will be achieved. Also, a simulation of the proposed fuzzy control system is performed in two modes for testing the effectiveness of the proposed fuzzy system. First mode consists of using the fuzzy simulation tool and the second mode consists in implementing of the fuzzy control system in the Simulink/Matlab.
Keywords: electric arc furnace, fuzzy controller, fuzzy logic, electric arc current, electric arc length

1. INTRODUCTION

Electric arc furnace (EAF) is important equipment and a high energy consumer in metallurgy. EAFs are used in the production of steel and are supplied by a special transformer.

The metal can be heated in the furnace tank directly by the three electrodes which are moving up and down, meanwhile, arc can be generated between every electrode and metal charging [1]. At the considered installation plant, the melting process is performed by direct action i.e. by electric arc that appears between the metal and the graphite electrodes.

EAFs are used in the steel industry in order to melt scrap or other metals into liquid steel. For the metallurgical reactions to take place, it is essential to achieve high temperatures in the furnace [2]. In order to do this, electric arcs are used which consume a lot of power, so, it requires to optimize the power delivered to the furnace. The arc power depends on the current and voltage of the electric arc. These are influenced by the electric arc length, which can be modified by means of the electrode positioning system. Therefore, it is important to control the electrodes movements, so that the desired power to be achieved.

In order to obtain the electric arcs, there are used three graphite electrodes which are supplied by a three-phase power transformer [3]. The three graphite electrodes are used to melt the metals that are loaded in the furnace tank, so different arc lengths exist in the melting stage, these lengths being a result of the random distribution of the metals in the furnace tank.

The electric arc is a nonlinear element, so, if one wants to study the behavior of a system containing an electric arc it must use techniques to model this nonlinearity [4]. Because of the dynamic behavior of the electric arc that appears during melting process of the metals, these furnaces are an important source of disturbances which must not be ignored. Therefore, solutions must be identified through which these disturbances should not be injected in the power supply network. At this network other equipment can be connected which can be influenced by these disturbances.

Due to power system problems attributed to EAFs, there has been an ongoing need for models that can be used to represent this type of nonlinear load in order to better assess the impact to EAF installations, whether existing, up-graded or new. The problem is complicated by the fact that the EAF voltage-current (v-i) characteristic is essentially much nonlinear.

Several known approaches for modeling and predicting the behavior of EAFs include the use of nonlinear resistance, mathematical, stochastic and system identification approaches, as well as methods based on v-i characteristic, power or current/voltage sources and a combination of thereof [5].

2. METHODOLOGY AND DISCUSSION - SYSTEM DESCRIPTION

EAF requires to be supplied with power in order to take place the chemical reactions. Figure 1 illustrates a block diagram of the electrical system of a typical EAF [6]. The three-phase transformer is the source of power for the furnace. Flexible cables are used for the connection between each phase of the transformer and the electrodes. These electrodes are supported by the electrode arms which are mounted on a hydraulic system that allows obtaining different arc lengths by changing the position of the electrodes. So, it is important to design an efficient control system of the EAF.

An EAF process cannot function without automatic control of the power, because of the random nature of the electric arc. Automatic control of an EAF should assure a corresponding operating of the EAF from the point of view of metallurgical process and of a high production.

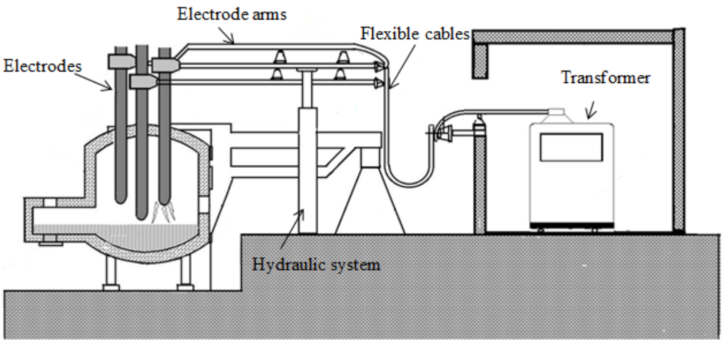

Figure 1. A block diagram of the EAF electrical system

The power level depends by the positions of the electrodes. As a result, the implementation of a competitive control system is very important because it led to reduction of the energy consumption, pollution, and increases the safety of the process [7].

Arc power can be controlled by modifying the power supply or by changing the electrodes position. First control is used for the passing from a technological stage to another, i.e. from the meltdown stage to the refining one. The second control is used to keep constant arc lengths during the same technological stage.

If the position of the electrodes is changed, different arc lengths will be achieved, so, different values for the arc current, arc voltage and arc impedance will be obtained too. Constant arc lengths imply that the electrical power to the arc furnace is stable around the reference value determined by the tap-changer of the furnace transformer.

In this paper, current control is the variable used to maintain a constant arc length. Arc current is mainly used as the control variable in an EAF because of its direct relation with the lengths of the electric arcs. The current controller adjusts the electric arc current, i.e. phase current, by modifying the arc lengths by the means of electrodes position.

If the electrodes are moved up, the arc length is increasing and so, the arc current is decreasing. Similarly, if the electrodes are moved down, it will be obtained a smaller arc length and so, the arc current is increasing.

By the actions that are influencing the arc lengths, so the arc current can be the following:

- The scrap temperature;
- The falling of the scrap that leads to short circuit;
- Shorting of the electrodes;
- Moving the arc because of the electrodynamics forces.

During a technological phase, the voltage of the secondary side of the furnace transformer is modified according to the technological specifications and the current is varying, because it depends by the arc length.

In summary, the process of the EAF involves the following characteristics: complexity, nonlinearity, variation and non-consistency, significant involvement of the human operator, need for expert operational knowledge and very noisy environment. These features justify application of intelligent techniques to EAF process modeling and control [8].

3. THE IMPLEMENTATION OF THE FUZZY LOGIC CONTROLLER

In this paper is proposed, designed and implemented a fuzzy current controller. Such a controller is important in an arc furnace industry, especially if short circuits occur during the arc furnace operation.

The control variable used in this paper is arc current, this strategy being known as current control. Using this strategy, the disturbances are rejected much faster than in case when other control variables are used. This is very desirable in an arc furnace industry, especially if the electrode tips make connections with the metallic charge and short circuits occur [9].

The structure of a fuzzy controller is composed by the knowledge base, the inference engine and the fuzzification and defuzification units as presented in figure 2.

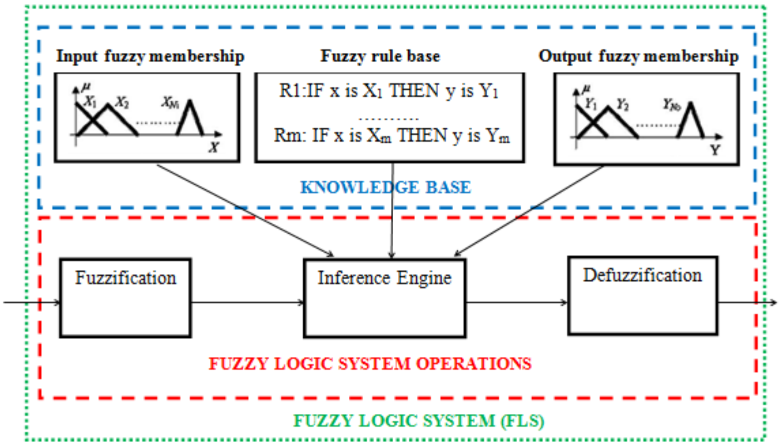

Figure 2. The fuzzy logic controller system

In order to design the fuzzy logic system (FLS) for the current control were chosen three inputs, namely the current deviation for the three phases and three outputs, namely electrode speed for the electrodes movement. In the considered installation plant, the electrodes are moved vertically, up or down, using hydraulic systems.

For the controller output was chosen the electrode speed, because it is easier to give the speed and the direction to which the electrodes should be moved to and not what position should the electrodes have to attend. Using a hydraulic system will be obtained the desired arc length, so desired arc current.

In figure 3 is presented the block diagram of the FLS, this system being designed in an intuitive manner, so, it has three inputs and three outputs, corresponding to the real plant.

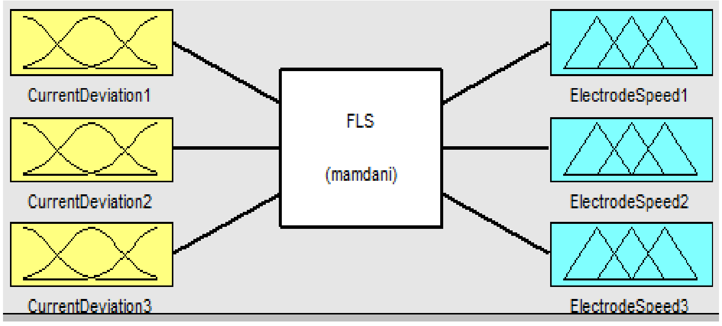

Figure 3. Block diagram of the FLS

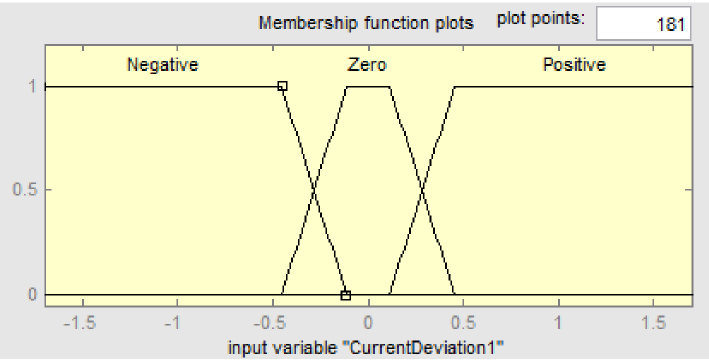

Figure 4. Membership functions for the input variable *Current Deviation*

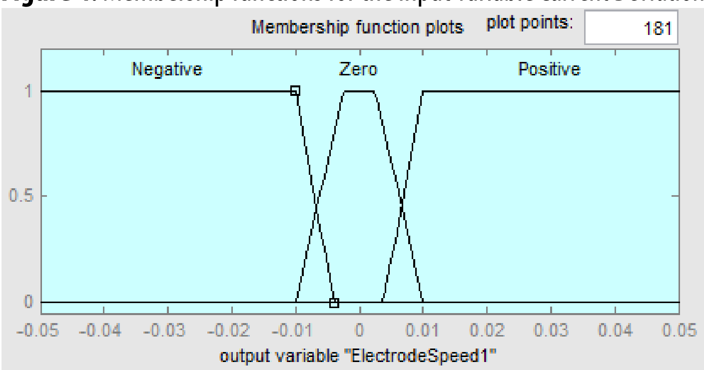

Figure 5. Membership functions for the output variable *Electrode Speed*

Figure 4 presents the membership functions for the input variable, namely arc current deviation. The universe of discourse for this variable is [-1.7, 1.7 KA] and is divided into three fuzzy sets. The membership functions used are trapezoidal. The linguistic variables are negative or positive depending by the current deviation which is the difference between the desired arc current and the measured arc current, obtained during of the EAF functioning. For each of the three input values of the fuzzy system were used the same universe of discourse, membership functions and linguistic variables. Therefore, in this paper are presented only the membership functions of the current deviation just for a phase of the furnace transformer.

Figure 5 presents the membership functions for the output variable, namely electrode speed. The universe of discourse for this variable is [-0.05, 0.05 m/s] and is divided into three fuzzy sets. The membership functions used are trapezoidal. The linguistic variables are negative or positive depending by the movement of the electrodes: down (negative) or up (positive). It was chosen this variable as the output of the fuzzy system because the arc current is influenced by the arc length. For each of the three output values of the fuzzy system were used the same universe of discourse, membership functions and linguistic variables. Therefore, in this paper are presented only the membership functions of the electrode speed needed to obtain only a desired arc current.

A fuzzy knowledge base consists of IF-THEN fuzzy rules and membership functions characterizing the fuzzy sets [2]. In this case, it is known the arc current deviation, as being the difference between the desired arc current and the obtained arc current. Depending on this value, the controller computes its output, i.e. electrode speed in order to move the electrode up or down with a specific speed. The electrodes position control is performed taking into account the real conditions that exist on the considered industrial plant. The maximum speed of the electrodes is of 3m/min (0.05 m/s) [10].

Because the fuzzy system has three inputs and three outputs, each with three fuzzy sets, the fuzzy current controller rules base consists of 27 rules that describe how must be moved the electrodes in order to have a desired arc current. In figure 6 are presented the rules base for the fuzzy system.

After the knowledge base is defined, can be applied the fuzzification operation, i.e. transform the numeric inputs into membership values. The inference engine, infer the output of the controller, so performs all fuzzy logic manipulators. It has as input fuzzy sets that were mapped from numeric values. The outputs of the fuzzy inference engine are also fuzzy sets so it is necessary to transform these into numeric values. This operation is named defuzzification.

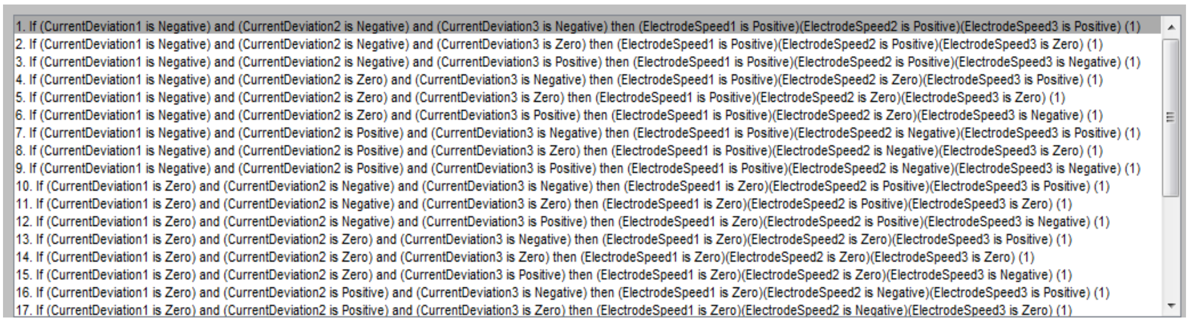
1. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Negative) and (CurrentDeviation3 is Negative) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Positive)(ElectrodeSpeed3 is Positive) (1)
2. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Negative) and (CurrentDeviation3 is Zero) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Positive)(ElectrodeSpeed3 is Zero) (1)
3. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Negative) and (CurrentDeviation3 is Positive) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Positive)(ElectrodeSpeed3 is Negative) (1)
4. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Zero) and (CurrentDeviation3 is Negative) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Zero)(ElectrodeSpeed3 is Positive) (1)
5. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Zero) and (CurrentDeviation3 is Zero) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Zero)(ElectrodeSpeed3 is Zero) (1)
6. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Zero) and (CurrentDeviation3 is Positive) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Zero)(ElectrodeSpeed3 is Negative) (1)
7. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Positive) and (CurrentDeviation3 is Negative) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Negative)(ElectrodeSpeed3 is Positive) (1)
8. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Positive) and (CurrentDeviation3 is Zero) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Negative)(ElectrodeSpeed3 is Zero) (1)
9. If (CurrentDeviation1 is Negative) and (CurrentDeviation2 is Positive) and (CurrentDeviation3 is Positive) then (ElectrodeSpeed1 is Positive)(ElectrodeSpeed2 is Negative)(ElectrodeSpeed3 is Negative) (1)
10. If (CurrentDeviation1 is Zero) and (CurrentDeviation2 is Negative) and (CurrentDeviation3 is Negative) then (ElectrodeSpeed1 is Zero)(ElectrodeSpeed2 is Positive)(ElectrodeSpeed3 is Positive) (1)
11. If (CurrentDeviation1 is Zero) and (CurrentDeviation2 is Negative) and (CurrentDeviation3 is Zero) then (ElectrodeSpeed1 is Zero)(ElectrodeSpeed2 is Positive)(ElectrodeSpeed3 is Zero) (1)
12. If (CurrentDeviation1 is Zero) and (CurrentDeviation2 is Negative) and (CurrentDeviation3 is Positive) then (ElectrodeSpeed1 is Zero)(ElectrodeSpeed2 is Positive)(ElectrodeSpeed3 is Negative) (1)
13. If (CurrentDeviation1 is Zero) and (CurrentDeviation2 is Zero) and (CurrentDeviation3 is Negative) then (ElectrodeSpeed1 is Zero)(ElectrodeSpeed2 is Zero)(ElectrodeSpeed3 is Positive) (1)
14. If (CurrentDeviation1 is Zero) and (CurrentDeviation2 is Zero) and (CurrentDeviation3 is Zero) then (ElectrodeSpeed1 is Zero)(ElectrodeSpeed2 is Zero)(ElectrodeSpeed3 is Zero) (1)
15. If (CurrentDeviation1 is Zero) and (CurrentDeviation2 is Zero) and (CurrentDeviation3 is Positive) then (ElectrodeSpeed1 is Zero)(ElectrodeSpeed2 is Zero)(ElectrodeSpeed3 is Negative) (1)
16. If (CurrentDeviation1 is Zero) and (CurrentDeviation2 is Positive) and (CurrentDeviation3 is Negative) then (ElectrodeSpeed1 is Zero)(ElectrodeSpeed2 is Negative)(ElectrodeSpeed3 is Positive) (1)
17. If (CurrentDeviation1 is Zero) and (CurrentDeviation2 is Positive) and (CurrentDeviation3 is Zero) then (ElectrodeSpeed1 is Zero)(ElectrodeSpeed2 is Negative)(ElectrodeSpeed3 is Zero) (1)

Figure 6. The rules base for the fuzzy system

4. TESTING OF THE FUZZY SYSTEM

In order to test the effectiveness of the proposed fuzzy system for the current control of a 3-phase EAF, the result obtained during the simulation will be presented in two modes.

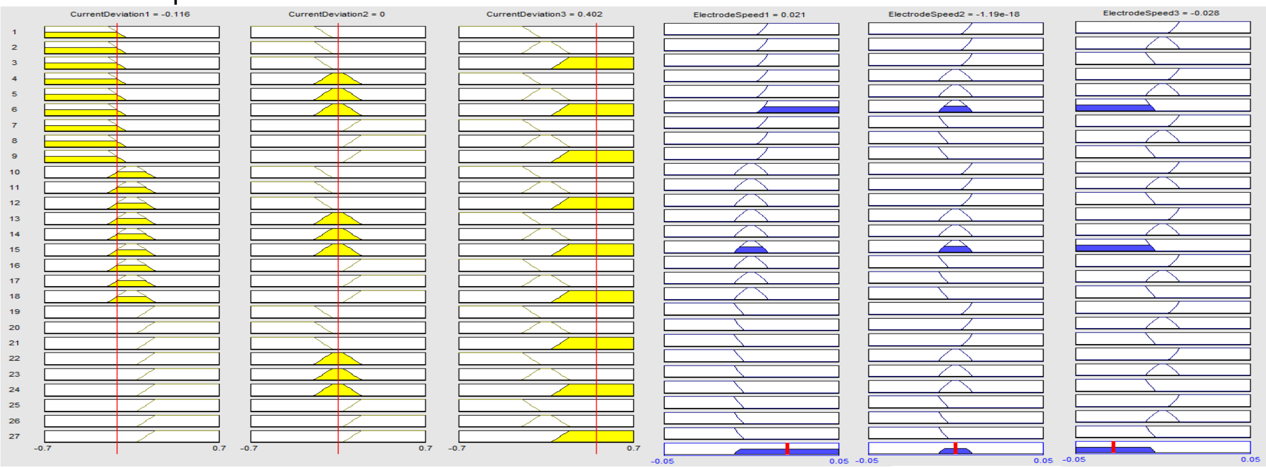

Figure 7. Simulating of the fuzzy system

First one is testing the fuzzy system using simulation tools from Matlab. So, in figure 7 are presented the active rules for a specific value of the inputs and are computed the outputs. The inputs of the FLS are the current deviation for each of the three phases of the furnace transformer. These deviations are computed as the difference between the desired arc currents and the measured ones. If the current deviation is negative, the measured current is larger than the desired one, so the current on the respective phase should be decreased. If the current deviation is positive, the measured current is smaller than the desired one, so the current should be increased. In order to obtain a larger current, electrode should be moved down and for a smaller current, electrode should be moved up. Taking into account the information previously presented, active rules from figure 7 can be noticed that:

- The current deviation for phase 1 is negative and zero with different degrees of the membership functions. This means that the measured current is larger than the desired one. Therefore, the electrode for the phase 1 must be moved up, in order to obtain a smaller electric arc current (electrode speed for phase 1 is positive in figure 7);
- The current deviations for phase 2 is approximately in the normal range, so the electrode from phase 2 should be stopped;
- The current deviation for the phase 3 is positive, this meaning that the measured current is smaller than the desired one. Therefore, the electrode for the phase 3 must be moved down, in order to obtain a larger electric arc current (electrode speed for phase 3 is negative in figure 7).

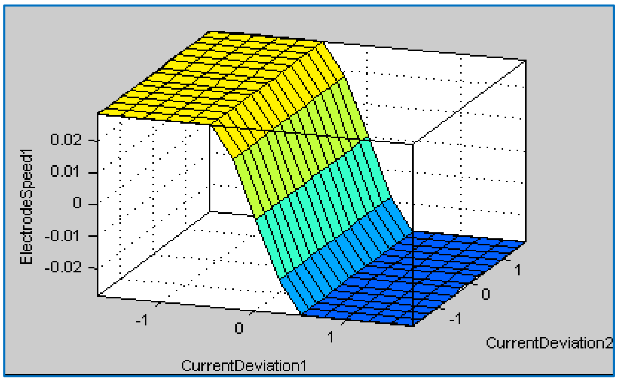

Figure 8. The surface obtained with the fuzzy system for two inputs and one output

Figure 8 shows the obtained surface with the simulation of the fuzzy system. Because in Matlab can be represented maxim 3D figures, the surface was designed for two inputs and one output. One can noticed that there are not discontinuities in the representation.

The second mode for testing this fuzzy system is to use Matlab-Simulink environment. In figure 9 is presented the implementation in Matlab-Simulink of the fuzzy system. Input variable values are randomly generated using a block that generates random values (random number), in order to simulate all possible cases. Variation of both input variables and output variables can be observed using an adequate block (Scope). Fuzzy Logic Controller block uses the fuzzy system previously presented.

In figure 10 are presented the values of the input variables *Current Deviation* for each of the three phases of the furnace transformer. These values are randomly generated.

In figure 11 are presented the values of the output variables *Electrode Speed* for each of the three phases of the furnace transformer. These values are computed by the fuzzy logic controller taking into account the implemented FLS. One can notice that the output values are in the range of (-0.05, 0.05) and have different speed for the movement of the electrodes.

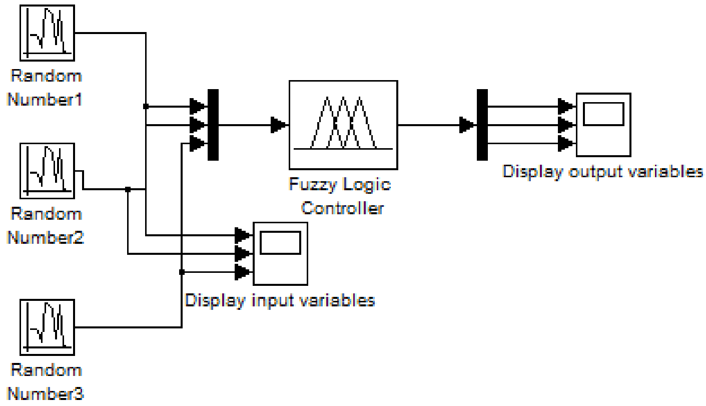

Figure 9. Implementation in Matlab-Simulink of the fuzzy system

These variations were obtained using the implementation of the model in Matlab-Simulink.

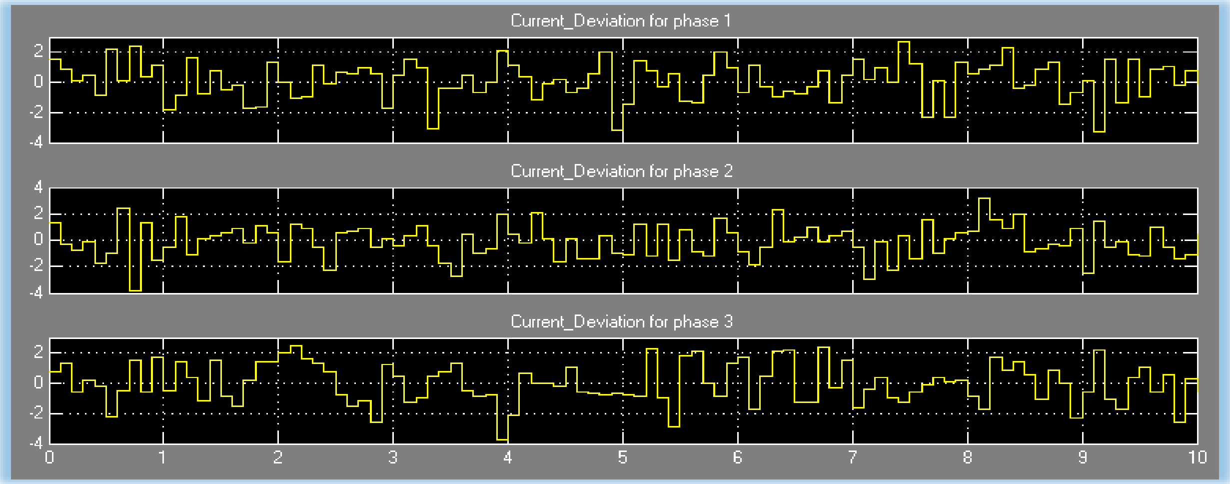

Figure 10. Visualization of the input variables for the fuzzy system

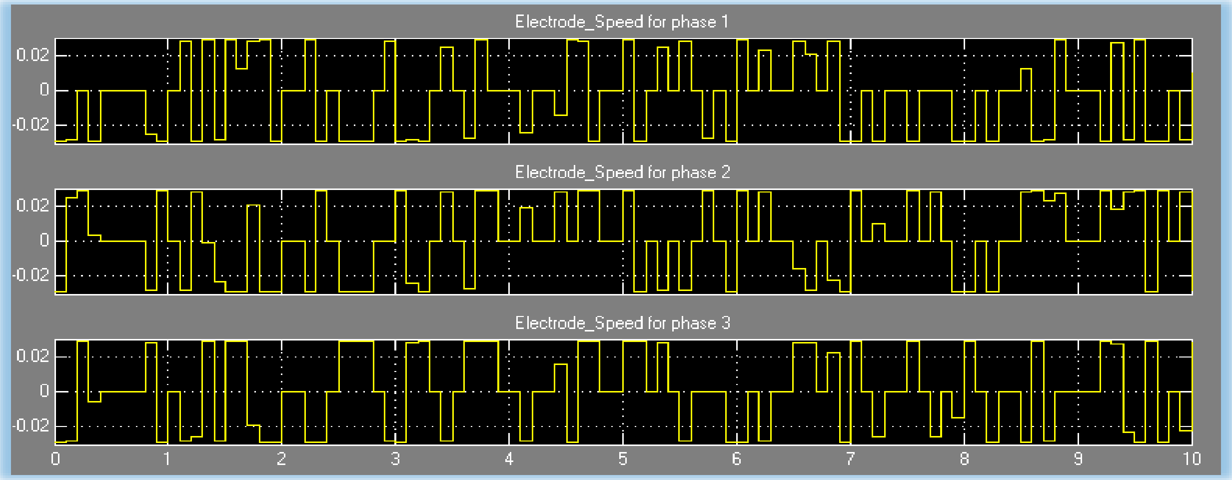

Figure 11. Visualization of the input variables for the fuzzy system

5. CONCLUSIONS

This paper presents a fuzzy current controller that is used to maintain constant arc lengths of the electric arcs. The purpose of this controller was to maintain the arc lengths as constant as possible by adjusting the vertical displacement of the EAF's electrodes.

In order to maintain a constant electrical power input, so a constant arc length, the phase currents that are the arc currents too, were used as the inputs for the controller.

The simulation results illustrate the effectiveness of the proposed fuzzy system for the current control of a 3-phase electric arc furnace.

References

[1.] Z. Hong, Y. Sheng, J. Li, M. Kasuga and L. Zhao, Development of AC electric arc-furnace control system based on fuzzy neural network, In Mechatronics and Automation, Proceedings of the 2006 IEEE International Conference on, June 2006, IEEE, pp. 2459-2464.

[2.] R.P. Paiva, Modelling and Control of an Electric Arc Furnace, Master Thesis, Lund Institute of Technology, Sweden, 1996.

[3.] R. Balan, O. Hancu and E. Lupu, Modeling and adaptive control of an electric arc furnace, IFAC Workshop ICPS'07 2007, July 09-11 Cluj-Napoca, Romania, 2007, pp. 163-168.

[4.] M. Panoiu, C. Panoiu, M. Osaci and I. Muscalagiu, Simulation Result about Harmonics Filtering using Measurement of Some Electrical Items in Electrical Installation on UHP EAF, WSEAS Transactions On Circuits And Systems, Volume 7, No. 1, January 2008, pp. 22-31.

[5.] M. Moghadasian, E. Alenasser, Modelling and Artificial Intelligence-Based Control of Electrode System for an Electric Arc Furnace, J. Electromagnetic Analysis Applications, 2011, 3: pp. 47-55.

[6.] M. Panoiu, C. Panoiu, Nonlinear processes modeling and simulation in electrothermics, Publishing House Mirton, Timisoara, 2008.

[7.] R. Balan, V. Maties, & S.D. Stan, Optimization of the Electrode Control System Using On Line Simulation and Rule Based Control, In Mechatronics and Automation, 2007, ICMA 2007, International Conference on, Harbin, China, 2007, pp. 2939-2944.

[8.] F. Janabi-Sharifi, and G. Jorjani, An adaptive system for modelling and simulation of electrical arc furnaces, in Control Engineering Practice, Vol. 17, No. 10, 2009, pp. 1202-1219.

[9.] M. Peens, "Modelling and control of an electrode system for a three phase electric arc furnace," Master's dissertation, University of Pretoria, Pretoria, 2006.

[10.] M. Panoiu, C. Panoiu and S. Deaconu, Study about the possibility of electrodes motion control in the EAF based on adaptive impedance control, In Power Electronics and Motion Control Conference, EPE-PEMC 2008, 13th. IEEE, 2008. pp. 1409-1415.

ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering