Fuzzy Logic Control of Three Phase Submerged Arc Ferrosilicon Furnace

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***Abstract* - Research is made into the fuzzy control of electrode regulator systems of submerged electrical arc ferrosilicon furnace EAF. The equations of the electrode currents and furnace resistances are derived based on certain model for the submerged arc ferrosilicon furnace. This model takes into consideration the walls of furnace and the heat losses into external medium in addition to the heat transfer of the system. The main purposes of the modelling are for the simulation and evaluations of different control schemes. In particular, the part of the system associated with the control of the three phase electrode currents, which is done by examining the positioning of the electrodes. The obtained results indicate that the developed simple linear model includes all critical factors needed in the simulation. Different electrode position based control schemes for electrode current control of the furnace is examined. The results of simulation show that fuzzy logic control systems have better dynamic characteristics than PD conventional control systems, and greatly strengthen the capability of restraining disturbances of arc length.**

***Index Terms* - Arc resistances, Models, Electrodes, Fuzzy control, Industrial process.**

1. Introduction

Ferrosilicon FeSi, which is an alloy of silicon (75%) and iron, is one of the basic raw materials in the steel industry [1-3]. Figure (1) shows a schematic diagram of a submerged arc furnace [4]. The raw materials (mainly quartz, coal and coke) are charged from the top into the cylindrical furnace shell. Three electrodes are submerged in the charge. An electrical arc creates the high temperature in the crater needed for the chemical reaction forming FeSi. The molten product is tapped through a tapping hole at the bottom of the furnace into a ladle. Typical arc furnaces operating data are 25 MVA, 120 V and 80 kA. The practical difficulties in mounting sensors and devices deep inside the furnace make the process unsuited for most direct measurements. Temperature as well as electrical conductance and current inside the furnace can be measured and monitored as control variables [4-7].

Several control strategies to furnaces in FeSi industry have been reported in the literature, see, e.g., [4] and references therein. These control strategies are mostly executed through positioning equipment consists of hydraulic hoists, which raise or lower each electrode separately on command. The electrode position is measured as the holder position in centimetres, measured from the lowest possible position.

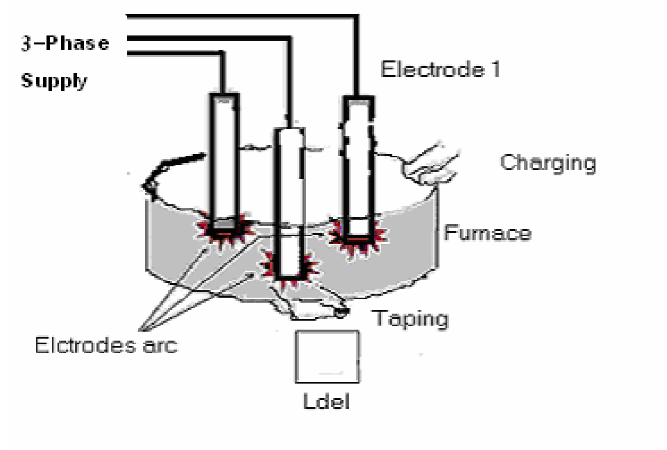

Figure (1) Schematic diagram of a submerged arc furnace

In this study a certain model of the arc FeSi furnace was designed. The model takes into considerations the walls of the furnace and the heat losses into external medium in addition to heat transfer of the system. A fuzzy logic controller with two inputs which are, the error in the V/I characteristic and the rate of the error in V/I characteristic is designed for submerged arc ferrosilicon furnace.

Fuzzy logic controller (FLC) techniques have been found to be a good replacement for conventional control techniques, owing to their low computational burden and ease of implementation using microcomputers [8]. The fuzzy-logic based controller overcomes system ambiguities and parameter variations by modelling the control objective based on a human operator experience, common sense, observation and understanding how the system responses, thereby eliminating the need for an explicit mathematical model for the system dynamics[8,9].

The present controller is effectively composed of three SISO (single input single-output) loops, each controlling one electrode current independently of the others. However, there is a considerable coupling between the electrodes [7]. The proposed fuzzy controller in this case is like PD fuzzy controller, for this reason to be fair; a comparison study was made with conventional PD controller.

2. ARC FURANCE SYSTEM MODEL

Figure (2) shows the interaction between the electrical and the metallurgical systems of the EAF. The electrical system supplies energy to the metallurgical system and the metallurgical system gives conductivity back to electrical system [2]. The electrical subsystem is described by a set of equations representing the electrical system, while the metallurgical subsystem is very different, as it involves gas and particle flow, reaction kinetics, etc. It is more difficult to establish a set of equations that describe the process to the relevant level of accuracy. To be successful in furnace modelling, it is very interesting to see the effect of the modularity shown in fig (2) with the two subsystems.

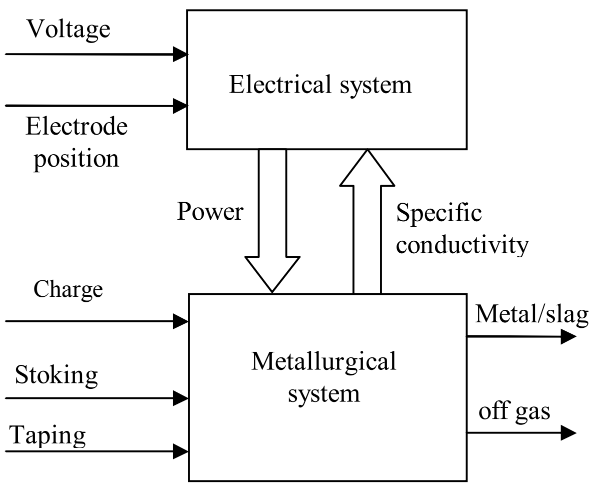

Figure (2) Complete model of the EAF system

There are many cases will be considered to model the arc furnace in this study:

1- The walls of furnace have ideal heat insulation and there are no losses of heat into external medium.
2- There are heat losses into external medium.
3- The walls of the furnace are great enough to reserve heat and be additional accumulator for heat.

2.1 IDEAL HEAT INSULATION FURNACE MODEL

The walls of the furnace have ideal heat insulation and there are no losses into surrounding. The equation of heat balance can be written as follows:

$$\rho CV\frac{d\theta}{dt} = H_1 - H_2 \qquad (1)$$

Where: r is the material density, ton/m^3, C is the specific heat, Mcal / deg .ton, V is the volume of the furnace, m^3, q is the temperature in zone, ^oC, $H_1 = Q_1 r_1 C q_1$ is the heat flow with material Q_1 Mcal/hour, Q_1 is the flow input m^3 /hour, $H_2 = Q_2 r_2 C q_2$ is the heat flow with material Q_2 Mcal/hour, Q_2 is the flow output m^3 /hour.

For simplicity Eqn. (1) can be reduced using the following assumptions:

i- $Q_1 = Q_2 = Q$ = const.
ii- The temperature $\theta(t)$ is equal to $q_2(t)$

Substituting these assumptions, Eqn. (1) can be reduced to the following transfer function

$$\frac{\theta(S)}{\theta_1(S)} = \frac{1}{TS+1} \qquad (2)$$

Where $T = \frac{V}{Q}$ is the time constant of the furnace.

Consider H_1 as input, the transfer function can be given as follows

$$\frac{\theta(S)}{H_1(S)} = \frac{K}{TS+1} \qquad (3)$$

Where $K=1/Q\,r\,C$ is the static gain of input.

2.2 HEAT LOSSES INTO SURROUNDINGS FURNACE MODEL

Consider the transfer of heat into external medium as follows:

$$H_3 = hS_w(\theta - \theta_{sp}) \qquad (4)$$

Where: h is the coefficient of heat transfer, S_w is the external surface of furnace, and θ_{sp} is the ambient temperature. $(\theta - \theta_{sp})$ is the difference between the temperature of the surface and the temperature of the external medium.

The balanced equation after adding the heat losses is given as follows

$$\rho CV\frac{d\theta}{dt} = H_1 - H_2 - H_3 \qquad (5)$$

By substituting Eqn. (4) into Eqn. (5), yields

$$T\frac{d\theta}{dt} + \theta = K_1\theta_{sp} + KH_1 \qquad (6)$$

Where K_1 is a static gain for disturbance.

Equation (6) represents a first order system showing the dynamic model of the furnace with heat losses in the surrounding.

2.3 MASSIVE WALL FURNACE MODEL

The heat capacity of the walls of the furnace is considered in the model. The walls of the furnace have a volume V_W (m^3), the material of the wall has density ρ_W and a specific heat capacity C_W [2,3].

The balance equation for the furnace space is [6,7]

$$\rho CV\frac{d\theta}{dt} = H_1 - QrCq_2 - h_w S_w(\theta - \theta_w) \qquad (7)$$

Where h_w is the heat transfer coefficient of the walls, and q_w is the wall temperature.

The balance equation for the walls can be represented by

$$r_w C_w V_w \frac{dq_w}{dt} = h_w S_w(q - q_w) - hS_w(q_w - q_{sp}) \qquad (8)$$

Substituting these assumptions q_2=q, variable H_1 as input and q is considered as output variable, the wall temperature θ_W can be calculated as follows

$$q_w = \frac{1}{h_w S}\left(rCV\frac{dq}{dt} - H_1 + QrCq \right) \quad (9)$$

By substituting Eqn.(9) into Eqn.(7), the furnace transfer function equation can be written as follows:

$$T_1T_2\frac{d^2\theta}{dt^2}+(T_1+T_2)\frac{d\theta}{dt}+\theta=KH_1+K_1\frac{dH_1}{dt}+K_2\theta_{sp} \quad (10)$$

Equation (10) can be written in Laplace transform as follows [1,2]

$$\theta(S)=\frac{(K+K_1S)H_1(S)+K_2\theta_{sp}(S)}{T_1T_2S^2+(T_1+T_2)S+1} \quad (11)$$

Where T_1, T_2, and K_2 are constants can be calculated using the parameters of the heat transfer model.

Equation (11) represents a second order system showing the dynamic model of the furnace with heat losses in the surrounding. Figure (3) represents a block diagram of a second order dynamic model of the furnace with heat losses in the surrounding. The two inputs are θ_{sp} and H_1, and a single output q.

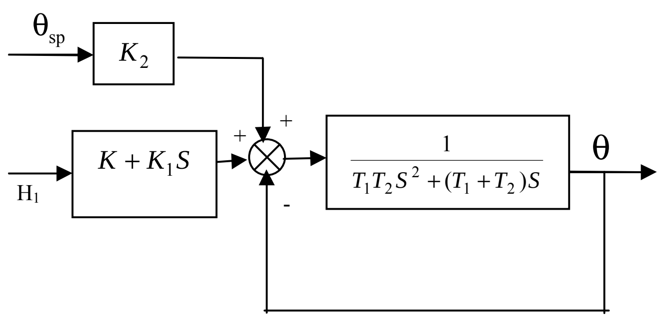

Figure (3) Heat transfer model for the electrical arc furnace

3. ARC FURANCE ELECTRICAL CIRCUIT ANALYSIS

3.1 PHYSICAL MODEL OF ARC FURNACE

Figure (4) shows a physical model of an electric arc furnace EAF with the three electrodes. The three electrodes are moved vertically up and down with hydraulic actuators. In theory, 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 it self [11].

The first step in the analysis of the electrical circuit is to use Kirchoff's Current Law (KCL) to equate currents and voltages. Figure (5) shows four nodes, one for each of the electrodes and the fourth representing the virtual ground at the matte V_m. Using these nodes; it is possible to determine the current in each electrode with respect to each voltage and the conductance coefficients. Applying KCL to the electrical model of fig. (5), the following sets of equations can be obtained;

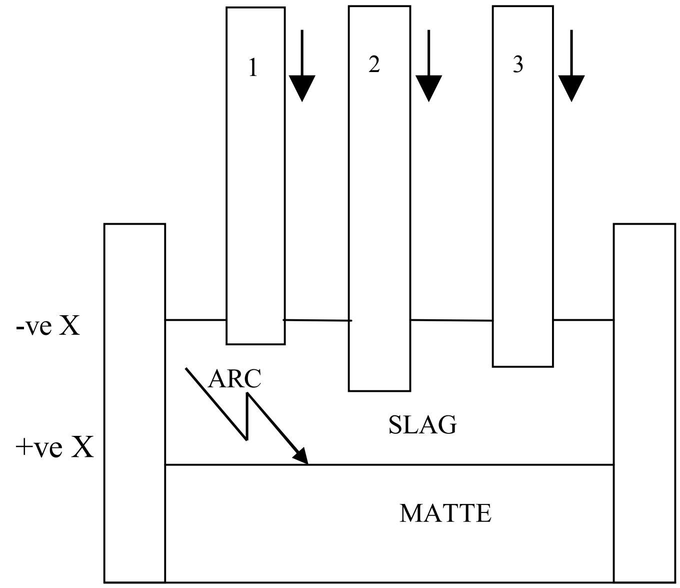

Figure (4) Physical model of EAF

$$[I_i] = [G_{ij}][X_i] + [B_i] \quad (12)$$

Equation (12) is a current matrix model. The outer resistances (inter-electrode resistances) form a delta circuit with the three nodes. The inner resistances (slag-to-matte resistances) form a wyes-connection with V_m as a virtual ground (floating neutral). Figure (5) shows the electrical model for the EAF with the chosen direction of currents [4]. To simplify calculations, the inter-electrode resistances are equivalent and represented by R. As for the slag-to-matte resistances, tests showed that these resistances displayed inverse linear relations with respect to their position. Consequently, by taking the slag-to-matte conductance, the inverse function becomes a linear relationship, which makes the calculations simpler. The slag-to-matte conductance's G_i, where i represent the electrode, can be written as [12]:

$$G_i = C_iX_i + G_s \quad (13)$$

Where: C_i is the conductance coefficient (in Siemens/m), X_i is the immersion depth of the electrode in the slag (in m) and G_s is the total conductance of the slag (in Siemens). In other words, G_s are the conductance of the slag when the electrodes are positioned at the surface of the slag.

$$\begin{aligned}
I_1 &= G_{12}(V_1 - V_2) + G_1(V_1 - V_m) + G_{13}(V_1 - V_3)\\
I_2 &= -G_{12}(V_1 - V_2) + G_2(V_2 - V_m) + G_{23}(V_2 - V_3)\\
I_3 &= G_3(V_3 - V_m) - G_{13}(V_1 - V_3) + G_{23}(V_2 - V_3) \quad (14)\\
&G_1(V_1 - V_m) + G_2(V_2 - V_m) + G_3(V_3 - V_m) = 0
\end{aligned}$$

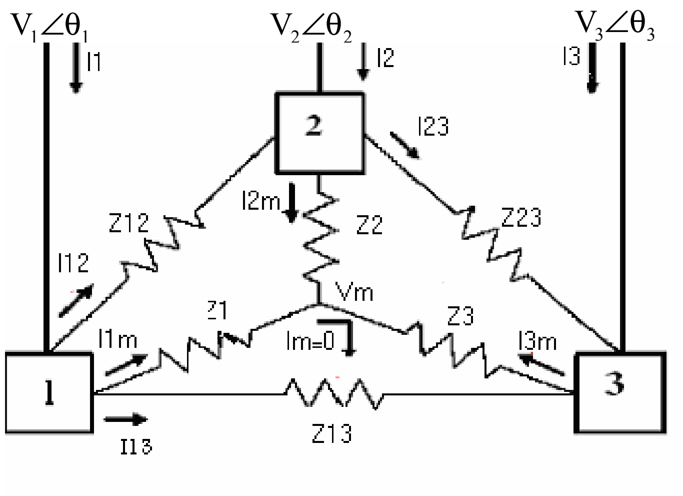

Fig (5) Electrical model of EAF

From Eqn. (14) V_m can be replaced by

$$V_m = \frac{G_1V_1 + G_2V_2 + G_3V_3}{G_1 + G_2 + G_3} \tag{15}$$

Due to the sin wave of the input voltage the equation of the current can be written as follows:

$$I_i(S) = \frac{V(S)}{(S - j\omega_0)(L_{arc}(q)S + R_{arc}(q))} \tag{16}$$

Where $\omega_o = 2\pi f/360$

The equation of the current in Laplace form is given as follows

$$I_1(S) = \frac{V_1 - V_m}{L_{arc}(\theta)S + R_{arc}(\theta)} + \frac{V_1 - V_m}{L_{12}(\theta)S + R_{12}(\theta)} + \frac{V_1 - V_m}{L_{13}(\theta)S + R_{13}(\theta)} \tag{17}$$

Where: $L_{arc}(\theta)$ and $R_{arc}(\theta)$ are the resistance and inductance under arc as a function in temperature [10, 13]. V's is the net applied voltage in electrode. $I_i(S)$ is the current of electrode i. The applied voltage effect on the electrode is given by

$$V_{applied} = V_s - V_{m\,(versioal\ node)} \tag{18}$$

Where $V_{applied}$ is actual applied voltage in electrode, V_s is the source voltage, and Vm is the voltage at versioal node. Figure (6) shows the closed loop system of the EAF with PD controller.

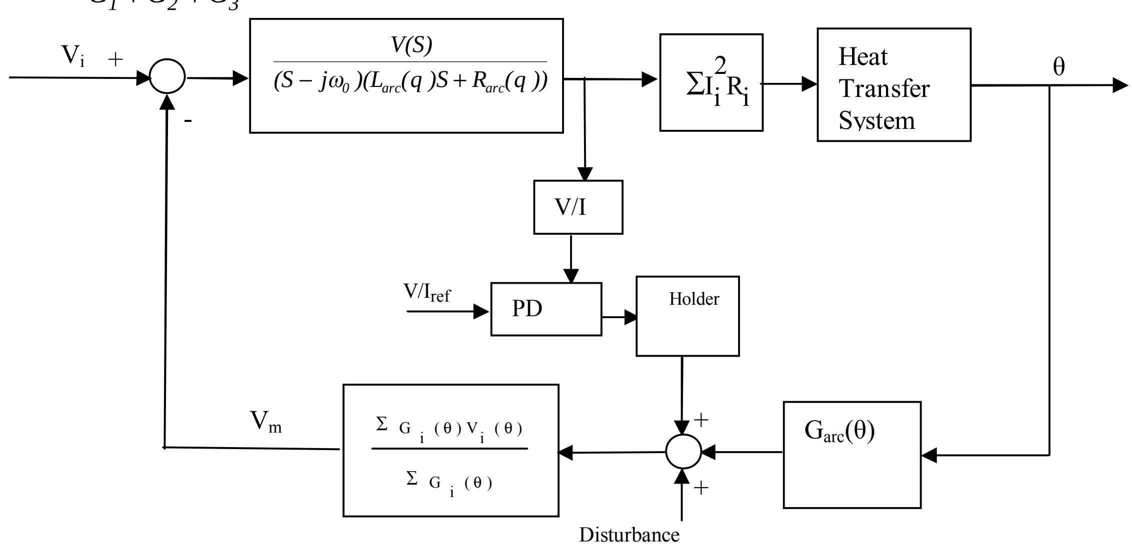

Figure (6) Closed loop system of EAF with PD controller

3.3 MODELLING OF THE ELECTRODE POSITION EQUIPMENT

The electrode positioning equipment were estimated and modelled as follows [5, 7]

$$G_{EL_{iup}}(s) = \frac{0.45e^{-ls}}{S(1.33S + 1)} \tag{19}$$

$$G_{EL_{idown}}(s) = \frac{1.1e^{-ls}}{S(2.5S + 1)} \tag{20}$$

4. FUZZY LOGIC CONTROLLER FOR SUBMERGED ARC FURANCE

4.1 EAF FUZZY LOGIC CONTROLLER MODELS (PD-CONTROLLER)

In this section the fuzzy logic technique is used as a PD controller as shown in fig. (7). The parameters of the EAF system under control are the temperature of the arc furnace and the input electrical power. But in our study the output of the arc furnace which is the V/I characteristic is used as input to the fuzzy logic controller and the input to the holder is the output of the fuzzy logic controller. The holder itself is a hydraulic system to adjust the position of the electrodes which control the V/I characteristic under the electrode.

The parameters K_e, $K_{e'}$ and K_u are stand for scaling factors of the error in V/I characteristic, rate of error in V/I characteristic and output of the controller, respectively. Block D stands for derivative.

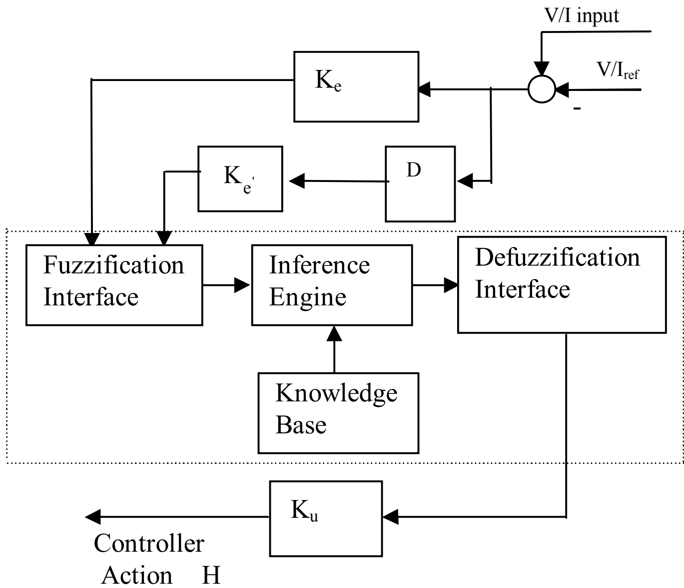

Figure (7) PD controller I/O description

The inputs to the fuzzy logic controller are selected to be the error of the V/I characteristic ΔV/I and the rate of the error ΔV/I' for one channel called fuzzy logic V/I defilation. The equation of sampling signal for input controller can derived using the following equation [8]:

$$\Delta V/I'(k) = \left(\frac{\Delta V/I(k) - \Delta V/I(k-1)}{\Delta t} \right) \quad (21)$$

Where Dt is the sampling interval (in our study equals to 0.001). It is clear that each value of the ΔV/I and ΔV/I' are passed through three stages; fuzzification stage, rules and inference stage, and defuzzification stage.

4.1.1 FUZZIFICATION

Having decided the inputs to the fuzzy logic controller, the next step is the fuzzification stage, where the input crisp variables ΔV/I(k) and ΔV/I'(k) are converted to fuzzy variables ΔV/I and ΔV/I'. Figure (8) shows the membership functions used in our study. One normalized universe of discourse (-1, 1) for ΔV/I, ΔV/I' and the output variable u_{EAF} is used. Each fuzzy universe of discourse is divided into ten fuzzy sets which are NL(negative large), NB (negative big), NM (negative medium), NS (negative small), NZ (negative zero), Z (zero), PZ (positive zero), PS (positive small) PM (positive medium), PB (positive big), PL (positive large). Each fuzzy variable is a member of the subset with a degree of membership μ(ΔV/I) and μ(ΔV/I') varying between 0 (non membership) and 1 (full membership) [9].

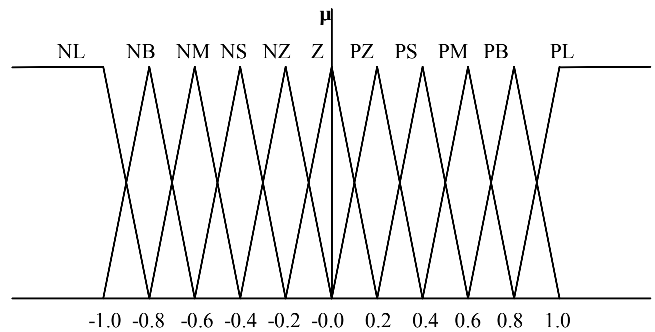

Figure (8) Fuzzy membership function

4.1.2 RULES CREATION AND INFERENCE

As mentioned before, the inputs to the fuzzy logic controller are the error of the V/I and the rate of the error ΔV/I'. For a system of two control variables with eleven linguistic variables in each range as explained in section 4.1.1, this leads to an 11x 11 decision table as shown in table (1) in appendix. The decision table is built according to the following concept with respect to the normalized phase plane [8]: the fuzzy control value is equal to zero on the main diagonal line, negative above diagonal line and positive below it. The fuzzy control value increases as the distance grows between the actual state and the hyper plane perpendicular to the switching hyper plane. ΔV/I and ΔV/I' that full out the phase plane space are covered by maximum fuzzy control value with its alternative sign.

A set of rules which based on the decision table define the relation between the input and output of the fuzzy variables ΔV/I and ΔV/I' produced by the fuzzification stages are then processed by an inference engine that executes a set of control rules. The inference engine maps the input variable to the universe of discourse of the output variable. A typical rule has the following structure:

R: if *(DV/I)* is PS and *(DV/I')* is PM then (u_{EAF}) is PM

Fuzzy rules are connected using AND operator and it was defined previously that AND operator means minimum value between μ (ΔV/I) and μ (ΔV/I'). Applying the operator AND for rule R, the minimum value between μ(ΔV/I) and μ(ΔV/I') can be found. Finally the corresponding output membership function for R is calculated by clipping the corresponding output triangle membership function (i.e. PM for R) this procedure is carried out for all the rules of the decision table shown in table (1) in the appendix and for every rule an output membership function is obtained.

4.1.3 DEFUZZIFICATION

The EAF final control system should be numerical signal so a non fuzzy signal is needed for control. This means that it should know the numerical value which refers to the membership function of the fuzzy controller. By using the central of gravity method, the crisp value of the output is obtained as

$$u_{EAF} = \frac{\sum_{i=1}^{n} y_i u(y_i)}{\sum_{i=1}^{n} u(y_i)} \quad (22)$$

Where n is the number of discrete values on the universe of discourse and m is the membership grade of the element y_i in the universe of discourse.

5. SIMULATION RESULTS TO 10% DISTURBANCE IN THE IMPEDANCE OF THE RAW MATERIAL

Figure (9-1) shows a 10% disturbance in the impedance of electrode 1. First the figure shows a value of impedance 2.44 mΩ then due to disturbance it down to 2.23 mΩ. The conventional PD controller raises the value to 2.34 mΩ with higher overshoot, while the fuzzy logic controller raises gradually the value of impedance to 2.23 mΩ with lower overshoot and fast settling time. Lower overshoot in the three phase submerged arc ferrosilicon furnace give the benefit of no hazard in the transformer circuit due to the lower impedance. Figure (9-2) shows the corresponding current responses of electrode 1 due to a 10% disturbance in the impedance of electrode 1. The steady state value of the current shows 58 KA; due to disturbance it reaches a higher value of 62.7 KA. With conventional PD it reaches 60 KA while with FLC it reaches 60.5 KA. In an EAF a large current fluctuations can cause the arc column to stretch to such an extent that the available power supply cannot maintain the arc. At this point, the arc extinguishes itself and reattaches to the electrode in such a manner as to minimize the initial ignition energy.

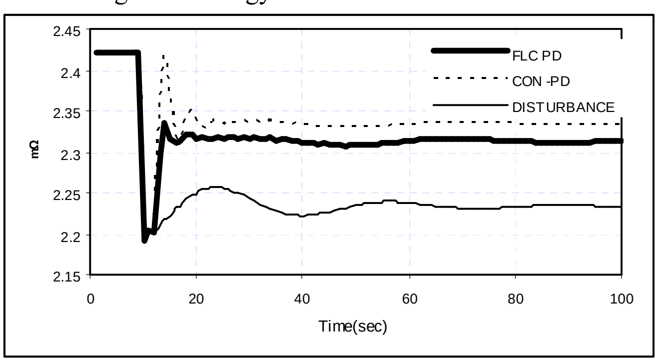

Figure (9-1) Impedance inside EAF electrode 1

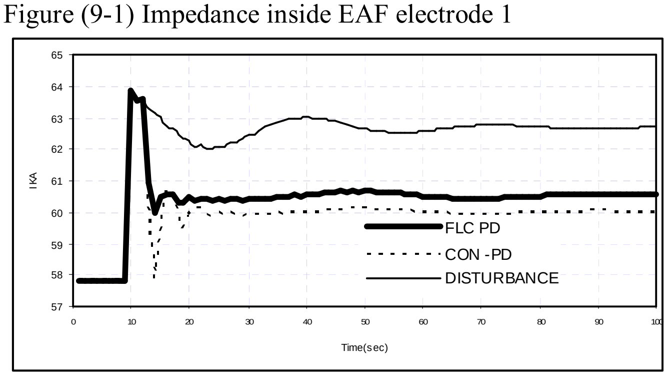

Figure (9-2) Current inside EAF electrode1

6. CONCLUSIONS

The applicability of fuzzy logic concepts to control a submerged arc ferrosilicon furnace is demonstrated. The model forming a submerged arc ferrosilicon furnace was successfully solved using C^{++} language program. This model describes heat transfer, which includes the raw materials, the wall of the furnace and heat losses into external medium. The models also include the electrodes position system which modelled the hydraulic system for up and down the electrode. A 10 parameter model was used to model the instantaneously time response of the current. Effectively, the obtained results indicate that the fuzzy logic controller raises gradually the value of impedance to a higher value with lower overshoot and fast settling time (i.e. which give the benefit of no hazard in the transformer circuit due to the lower impedance). Also in an EAF a large current fluctuations can cause the arc column to stretch to such an extent that the available power supply cannot maintain the arc. At this point, the arc extinguishes itself and reattaches to the electrode in such a manner as to minimize the initial ignition energy.

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APPENDIX

Table (1) Rules creations table

		Rate Of V/I Deviation										
		NL	NB	NM	NS	NZ	Z	PZ	PS	PM	PB	PS
V/I Deviation	NL	NL	NL	NL	NL	NL	NL	NB	NM	NS	NZ	Z
	NB	NL	NL	NL	NL	NL	NB	NM	NS	NZ	Z	PZ
	NM	NL	NL	NL	NL	NB	NM	NS	NZ	Z	PZ	PS
	NS	NL	NL	NL	NB	NM	NS	NZ	Z	PZ	PS	PM
	NZ	NL	NL	NB	NM	NS	NZ	Z	PZ	PS	PM	PB
	Z	NL	NB	NM	NS	NZ	Z	PZ	PS	PM	PB	PL
	PZ	NB	NM	NS	NZ	Z	PZ	PS	PM	PB	PL	PL
	PS	NM	NS	NZ	Z	PZ	PS	PM	PB	PL	PL	PL
	PM	NS	NZ	Z	PZ	PS	PM	PB	PL	PL	PL	PL
	PB	NZ	Z	PZ	PS	PM	PB	PL	PL	PL	PL	PL
	PL	Z	PZ	PS	PM	PB	PL	PL	PL	PL	PL	PL