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MODELING AND SIMULATION OF FUZZY PID CONTROLLERS FOR A SUBMERGED ARC FERROSILICON FURNACE

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This paper investigates the control strategy for the electrical energy input to three phase electric arc ferrosilicon furnace. The classical PD fuzzy logic controller has two inputs. These inputs are the error in the V-I characteristic and the rate of the error in V-I characteristic. When the simulation result of this controller is compared with conventional PD type, it was shown that requires steady state accuracy. This paper is concerned with incorporating the integral property to the classic fuzzy PD controller. The result is a nonlinear fuzzy PID controller eliminates the steady state error resulted from the classic fuzzy PD actions. In this paper, the submerged arc ferrosilicon furnace is described by the heat transfer system, the electrical system equipments and the dynamics from the electrode positions to the electrode currents. The proposed control design methodology is tested on the model of submerged arc ferrosilicon furnace FeSi via simulation. The simulation work is carried out using simple environment via computer program written using C++ language. The obtained results guarantee the potential of the proposed control methodology to add self autonomy to the system behavior.

KEYWORDS: *Arc resistances; Electrodes; Fuzzy Logic control; Industrial process, Model; PID controllers.*

1. INTRODUCTION

Electric arc furnaces are used to produce *FeSi* by melting the raw materials (mainly quartz, coal, and coke) using electrical supply as main energy input [1-6]. The electrode system, connected to the electrical supply as shown in Fig. (1) is used to convert electrical energy into extensive heat by means of high current arcs cause the solid scrap to be transformed into liquid state.

The main objective in an electric arc furnace industry is maximum production of high quality *FeSi* at the lowest possible cost. Electric current in the electrodes will remain constant if the lengths of the electric arcs are constant. The electrode system under investigation in this study is mainly responsible for the vertical adjustments of the electrode tip displacement according to specified set points, to ensure that the arc lengths remain as constant as possible. Arc current is mainly used as the control variable in an industrial electric arc furnace because of its direct relation with the lengths of the electric arcs.

Most modern three-phase electric furnaces make use of some form of feedback control strategy for the automatic control of the electrical energy input [7-15]. One of the control strategy utilized is the use of *PID* controllers which can adjust the lengths of the electric arcs relative to some set-point. *PID* controller is well established in many classical control systems and it is often used as a benchmark against other types of controllers [16]. *PID* controllers are considered as linear controller, for this reason it is not usually suitable for strongly nonlinear systems. Fuzzy *PID* controllers are often mentioned as an alternative to classical fuzzy *PD* controllers in such cases [17-19].

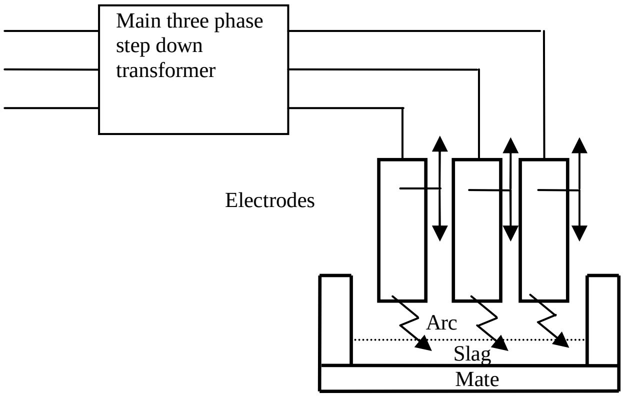

Fig. (1) A Physical model of EAF system

Fuzzy *PID* controllers used in a submerged arc ferrosilicon furnace are found in [20]. Various structures for fuzzy *PID* (including *PI* and *PD*) controllers are found in [21, 22]. Fuzzy *PI* control is known to be more practical than fuzzy *PD* because it is difficult for the fuzzy *PD* to remove steady state error [23]. The fuzzy *PI* control, however, it gives poor performance in transient response for higher order processes due to the internal integration operation, but it eliminates the steady state error resulted from the proportional gain. Thus, in practice the fuzzy *PID* controllers are more useful. To obtain proportional, integral and derivative control action all together, it is intuitive and convenient to combine *PI* and *PD* actions together to form a Fuzzy *PID* controller. Another way of constructing a fuzzy *PID* controller is achieved by summing the fuzzy *PD* controller output to an integrator connected in parallel with it [22]. This fuzzy *PID* controller utilized a single rule-base. In this paper the second type is used in our study.

2. ARC FURNANCE SYSTEM MODEL

There are two subsystems in the electrical arc furnace, electrical and metallurgical system. The electrical system supplies energy to the metallurgical system and the metallurgical system gives conductivity back to electrical system [1]. 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 [2, 3]. In modeling the electric arc furnace, many factors are to be considered. These are heat transfer, walls of furnace and the heat losses into external medium.

- The walls of the furnace have ideal heat insulation and there are no losses into surrounding. The transfer function of heat balance is as follows:

$$\rho CV\frac{d\theta}{dt}=H_1-H_2 \tag{1}$$

Where: ρ is the material density, ton/m^3, C is the specific heat, Mcal / deg .ton, V is the volume of the furnace, m^3, θ is the temperature in zone, $^\circ c$, $H_1=Q_1\rho_1C\theta_1$ is the heat flow with material Q_1 Mcal/hour, Q_1 is the flow input m^3 /hour , $H_2=Q_2\rho_2C\theta_2$ is the heat flow with material Q_2 Mcal/hour , Q_2 is the flow output m^3 /hour. The material flow for input and output are assumed to be constant (Q_1 $=Q_2=Q$) and the temperature $\theta(t)$ is equal to $\theta_2(t)$.

$$\frac{\theta(S)}{H_1(S)}=\frac{K}{TS+1} \tag{2}$$

Where $T=\frac{V}{Q}$ is the time constant of the furnace, $K=\frac{1}{Q\rho C}$ is a static gain.

- Consider the transfer of heat into external medium as follows:

$$H_3=hS_w(\theta-\theta_{sp}) \tag{3}$$

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 external medium.

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

$$\rho CV\frac{d\theta}{dt}=H_1-H_2-H_3 \tag{4}$$

Substituting Eq.(3) into Eq.(4) we get

$$T\frac{d\theta}{dt}+\theta=K_1\theta_{sp}+KH_1 \tag{5}$$

Where K_1 is a static gain for disturbance.

- The heat capacity of the walls of the furnace is to be taken into consideration in the model. The walls of the furnace has 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 [6, 7]

$$\rho CV\frac{d\theta}{dt}=H_1-Q\rho C\theta_2-h_wS_w(\theta-\theta_w) \tag{6}$$

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

The balance equation for the walls can be represented by

$$\rho_wC_wV_w\frac{d\theta_w}{dt}=h_wS_w(\theta-\theta_w)-hS_w(\theta_w-\theta_{sp}) \tag{7}$$

Substituting these assumptions $\theta_2=\theta$, variables H_1 as input and θ is considered as output variable, the wall temperature θ_W can be derived as follows:

$$\theta_w=\frac{1}{h_wS}\left(\rho CV\frac{d\theta}{dt}-H_1+Q\rho C\theta\right) \tag{8}$$

Substituting Eq.(8) into Eq.(6) the furnace transfer function equation can be written as follows:

$$T_1T_2\frac{d^2\theta}{dt^2}+(T_1+T_2)\frac{d\theta}{dt}+\theta = KH_1+K_1\frac{dH_1}{dt}+K_2\theta_{sp} \tag{9}$$

Eq.(9) in laplace transform is as follows [1,2]

$$\theta(S) = \frac{(K+K_1S)H_1(S)+K_2\theta_{sp}(S)}{T_1T_2S^2+(T_1+T_2)S+1} \tag{10}$$

Where, T, T_1, T_2, K, K_1 and K_2 are constants which are calculated by the use of the parameters of the heat transfer model. Eq. (10) represents the dynamic model of the furnace with heat losses in the surrounding. Figure (2) represents a block diagram of Eq. (10). The two inputs are ambient temperature θ_{sp} and the input heat flow H_1 and a single output θ.

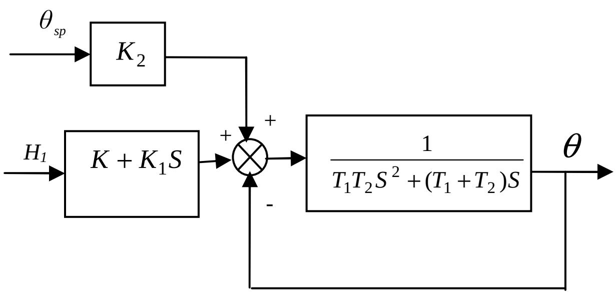

Fig. (2) Heat transfer model for the electrical arc furnace

2.1. Summary of the Heat Transfer Modeling Parameters

The parameters of the heat transfer model can be derived by the use of Eq. (1) to Eq. (10) and are shown in Table [1] as follows:

Table [1] Heat transfer model parameters

Parameter	Math calculation of parameter
$T_1\ T_2$	$\dfrac{\rho CV\ \rho_w C_w V_w}{h_w S_w\left(\rho CQ+\dfrac{h\rho CQ}{h_w}+hS_w\right)}$
T_1+T_2	$\dfrac{\dfrac{\rho CV\rho_w C_w V_w}{h_w}+\rho_w C_w V_w+\rho CV+\dfrac{h\rho CV}{h_w}}{\rho CQ+\dfrac{h\rho CQ}{h_w}+hS}$
K	$\dfrac{1+h/h_w}{\rho CQ+\dfrac{h\rho CQ}{h_w}+hS_w}$
K_1	$\dfrac{\rho_w C_w V_w}{h_w S_w\left(\rho CQ+\dfrac{h\rho CQ}{h_w}+hS_w\right)}$
K_2	$\dfrac{hS_w}{\left(\rho CQ+\dfrac{h\rho CQ}{h_w}+hS_w\right)}$

3. ARC FURNANCE ELECTRICAL SYSTEM

The moving of the electrodes inside the arc furnace up and down above the slag creates the arc phenomenon. As the electrodes approach the slag, a huge value of current jumps from the electrodes to the slag. The arcing distance depends mainly on the magnitude of the input voltage. The heating power P_{hi} of the arc for electrode *i* depends on the value of the voltage and the conductance G_i of the arc.

$$P_{hi} = V_{arci}^2 G_i \tag{11}$$

The conductance of the arc for electrode *i* depends on the physical properties of the raw materials and the geometrical dimensions of the arc of electrode i. This is given as:

$$G_i = \sigma \frac{a_i}{\ell_i} \tag{12}$$

Where σ is the conductivity of the material being heated, a_i *and* l_i are the geometrical dimensions of the body. The electrical conductivity of the raw materials is varying creates the gas mixture in the furnace. The column path depends on the ratio a_i / ℓ_i which is relatively large. According to the above analysis, the gas mixture in the furnace creates the arc resistance. Therefore to maintain a given power according to specified heating conditions, it is necessary to change the voltage supplied in wide range.

The equation of the source voltage transient response of the electrical arc furnace is given as:

$$V_s = L\frac{dI}{dt} + IR + V_{arc} \tag{13}$$

Where V_s voltage source, V_{arc} arc voltage and L, R are inductance and resistance of the conductor.

The practical difficulty in mounting sensors and devices deep is inside the furnace that makes the process unsuited for most direct measurements. A related temperature to electrical conductance and current inside the furnace can be measured and controlled as control variables which are the *V-I* characteristic inside the arc furnace. The conductance in the furnace as function in temperature is given as follows [1];

$$G(\theta) = G_0(1 - exp(0.5 - \theta/100)) \tag{14}$$

Where G_0 is the conduction at 25^0

3.1. Composing the Heat Transfer Model with Electrical System

There are two subsystems in the electric arc furnace EAF. The first is the heat transfer subsystem (discussed in section 2), the other one is the electrical parts. The next step is to link these two subsystems. To do this, the following steps are taken to make the complete electrical arc furnace model:

a. The input of the heat transfer model is electrical power.
b. The heat transfer model output is temperature inside the furnace.

c. The temperature inside the furnace affects the electrical resistance of the furnace.
d. The resistance inside the furnace affects the electrical parameters inside the furnace such as voltage under arc, current and power delivered to the furnace.
e. The electrical power depends on the voltage applied to the arc furnace, resistance-inductance of the conductors and the resistance-inductance inside the furnace.
f. Neglect the chemical reaction inside the furnace.

3.2. Voltage-Current Ratio as a Control Variable in the Arc Furnace

Figure (3) shows the closed loop system of the EAF equipped with *PID* control. The input to the controller is *V-I* characteristic and the output of the furnace is the conductance as a function in θ.

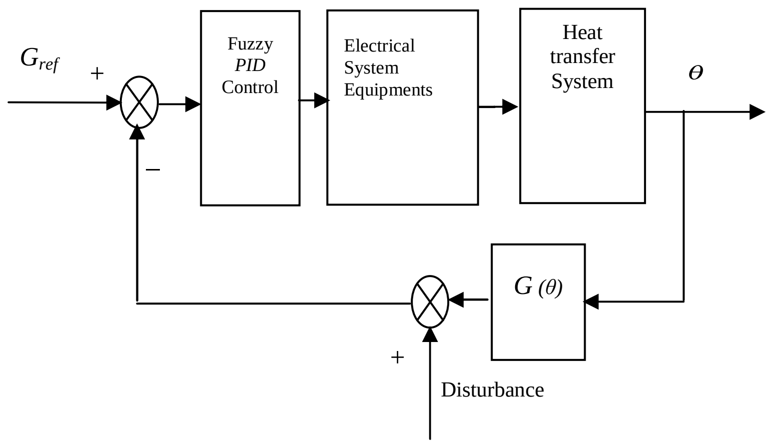

Fig. (3) Closed loop system of the EAF with PID control.

4. FUZZY LOGIC CONTROLLER FOR SUBMERGED ARC FURNANCE

4.1. Classical Fuzzy Logic Controller for EAF

In this section the fuzzy logic technique is used as a *PD* controller as shown in Fig. (4).The parameters of the EAF system under control are the temperature of the arc furnace and the input electrical power. In this study, the output of the arc furnace is considered as the *V-I* characteristic as mentioned in section 3. This output is used as input to the fuzzy logic controller. The input to the hydraulic system is the output of the fuzzy *PD* controller. The hydraulic system is called a holder and is used to move the electrodes up and down to adjust their positions. The parameters F_e, $F_{e'}$ and F_u stand for scaling factors of the error e, rate of error e' and the output of the controller, respectively. The inputs to the fuzzy logic controller are selected to be the error of the *V-I* characteristic which is called e and the rate of the error e'. Sampling signal for input controller equation is to be written as follows:

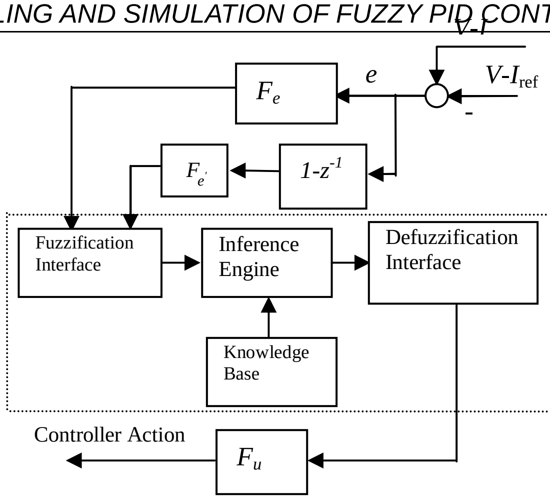

Fig. (4) PD controller I/O description

$$e'(k) = \left(\frac{e(k) - e(k-1)}{\Delta\tau} \right) \tag{15}$$

$$e'(k) = e(k)\left(\frac{1 - z^{-1}}{\Delta\tau} \right) \tag{16}$$

Where $\Delta\tau$ is the sampling interval (in our study equals to 0.001). The design of a fuzzy logic controller passes through the following stages: selection of input/output variables and their quantization in fuzzy sets, this stage called fuzzification; selection of the inference method; selection of the defuzzification technique.

4.2. Fuzzification

Having decided the inputs to the fuzzy logic controller, the next step is the selection of the membership functions to be associated with the input/output variables, where the input crisp variables $e(k)$ and $e'(k)$ are converted to fuzzy variables. Figure (5) shows the membership functions used in this study. One normalized universe of discourse (-1, 1) for e, e' and the output variable u_{EAF} is used. Each fuzzy universe of discourse is divided into eleven fuzzy sets:

- *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

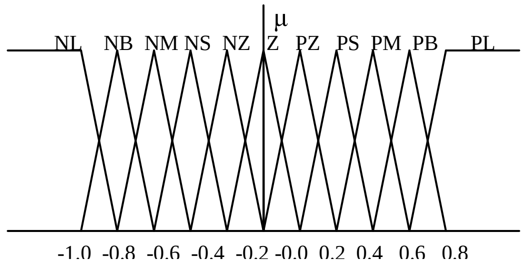

Fig. (5) Fuzzy membership function

4.3. Rules Creation and Inference

As stated before, the inputs to the fuzzy logic controller are the error e and the rate of the error $e^{'}$. For a system of two control variables with eleven linguistic variables in each range as explained in section *4.2*, this leads to an *11x 11* decision table as shown in Table [2]. A set of rules which based on the decision table defines the relation between the input and output of the fuzzy variables e and $e^{'}$ produced by the fuzzification stages. These 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:

If (e) is PS and $(e^{'})$ is PM then (u_{EAF}) is PM (17)

Fuzzy rules are connected using *AND* operator and it was defined as minimum value between μ (e) and μ $(e^{'})$. Applying the operator *AND* to the rule given by Eq. (17), the minimum value between $\mu(e)$ and $\mu(e^{'})$ can be derived. Finally the corresponding output membership function for the rule defined by Eq. (17) is calculated by clipping the corresponding output triangle membership function (i.e. *PM*). This procedure is carried out for all the rules of the decision table shown in Table [2] and for every rule an output membership function is obtained. Fig.(6) shows the flow chart of the digital computer program used for simulation of an EAF provided with fuzzy *PID* controller.

Table [2] Rules creations table

		e'										
		NL	**NB**	**NM**	**NS**	**NZ**	**Z**	**PZ**	**PS**	**PM**	**PB**	**PS**
e	**NL**										**NZ**	**Z**
	NB									**NZ**	**Z**	**PZ**
	NM								**NZ**	**Z**	**PZ**	
	NS					**NM**	**NS**	**NZ**	**Z**	**PZ**		
	NZ				**NM**	**NS**	**NZ**	**Z**	**PZ**	**PS**	**PM**	
	Z			**NM**	**NS**	**NZ**	**Z**	**PZ**	**PS**	**PM**		
	PZ			**NS**	**NZ**	**Z**	**PZ**	**PS**	**PM**			
	PS			**NZ**	**Z**	**PZ**	**PS**	**PM**				
	PM		**NZ**	**Z**	**PZ**	**PS**	**PM**					
	PB		**Z**	**PZ**	**PS**	**PM**						
	PL	**Z**	**PZ**	**PS**	**PM**							

4.4. Defuzzification

It is necessary to transform the implied fuzzy set to a crisp output by the center of gravity technique as given by the Eq. (18), where v_i is the numerical output at the ith number of rules and $\mu(v_i)$ corresponds to the value of fuzzy membership function at the ith number of rules. The summation is from one to n, Where n is the number of discrete values on the universe of discourse and μ is the membership grade of the element v_i in the universe of discourse [24].

$$u_{EAF} = \frac{\sum_{i=1}^{n} v_i u(v_i)}{\sum_{i=1}^{n} u(v_i)} \tag{18}$$

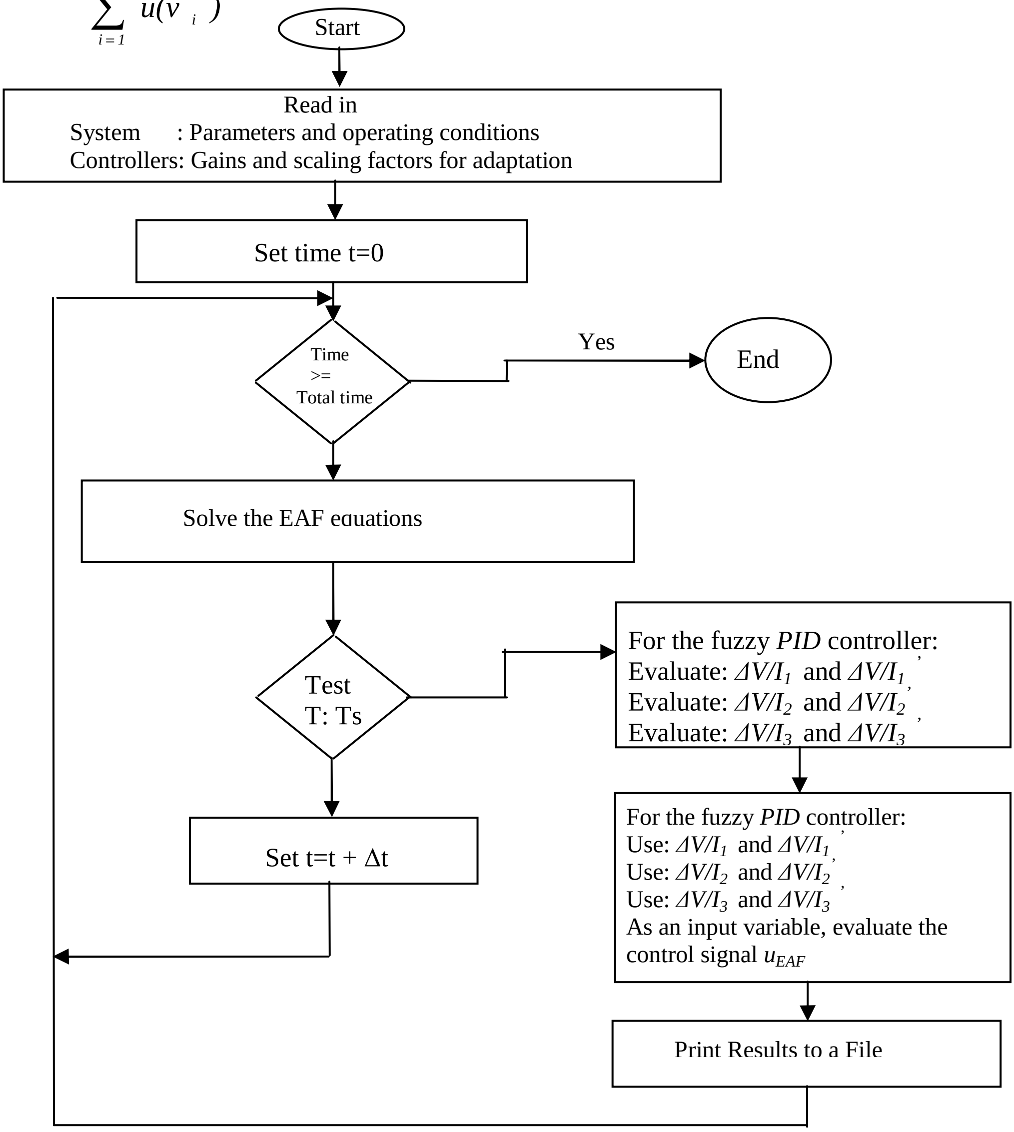

Fig. (6) Flow chart of the computer program used for simulation of an EAF provided with fuzzy *PID* controller

5. PROPOSED FUZZY PID CONTROLLER FOR A SUBMERGED ARC FERROSILICON FURNACE

The input-output relation of the conventional *PID* controller is given as;

$$u = K_p e + K_I \int edt + K_D e' \tag{19}$$

The performance of that controller is determined by adjusting the parameters K_P , K_I and K_D. The proportional parameter can guarantee the fast response of the control system, the integral parameter can eliminate the steady state error of the control system, and the derivative parameter can increase the damping of the control system. The fuzzy logic controller explained in section 4 is approximately behaved like a parameter time varying *PD* controller. But obviously, there would be steady state error by using fuzzy *PD* type controller. The input-output relation of the fuzzy *PD* type controller can be approximated by [25];

$$u_{EAF} = A + Pe + De' \tag{20}$$

The integral property of the fuzzy logic controller can be handled by implementing the integration of the system's error through the inputs of the fuzzy logic controller. The observation of the system's integral error is very difficult task in practice because more fuzzy control rules are needed. Hence, it is better to design a fuzzy controller by using the outputs of the fuzzy *PD* controller. Utilizing the output relation given by Eq. (20), a fuzzy *PID* controller can be designed. Let an integrator be connected serially with a portion of the output of the fuzzy *PD* controller as shown in Fig. (7). The structure of the proposed fuzzy controller is simply connected the *PD* type fuzzy controller together in parallel with an integrator. The output of the fuzzy *PID* controller considering α as the weight on the *PD* type, and β as the weight on the *PI* type can be approximated by the following [25];

$$u'_{EAF} = \alpha u + \beta \int udt \tag{21}$$

By substituting Eq. (21) into Eq. (20), the following equation can be obtained;

$$u'_{EAF} = \alpha(A + Pe + De') + \beta \int (A + Pe + De')dt \tag{22}$$

Rearranging Eq. (22) yields

$$u'_{EAF} = \alpha A + \beta At + (\alpha P + \beta D)\, e + \beta P \int edt + \alpha De' \tag{23}$$

Considering the scaling factors used in section 4.1, Eq. (23) can be written as;

$$u'_{EAF} = \alpha A + \beta At + (\alpha P + \beta D)\, F_e\, e + \beta F_e\, P \int edt + \alpha D F_{e'}\, e' \tag{24}$$

Eq. (24) behaves like a time varying *PID* controller, its equivalent to proportional plus integral plus derivative control and the parameters are simply given as follows;

$K_P = (\alpha P + \beta D)\, F_e$, $K_I = \beta F_e P$, $K_D = \alpha F_{e'} D$

For *PI* controller

$\alpha = 0$, $\beta > 0$

$$u = \beta At + \beta F_{e'} De + \beta F_e P \int edt \tag{25}$$

For *PD* controller

$\alpha > 0,\ \beta = 0$

$$u = \alpha A + \alpha F_e P + \alpha F_{e'} e' \tag{26}$$

The integral property of the fuzzy controller can be handled by implementing the integration of the system's error through the inputs of the fuzzy *PD* controller discussed in section 4. The observation of the system's integral error is very difficult task in practice because more fuzzy control rules are needed. Hence, it is better to design a fuzzy controller by using the outputs of the fuzzy *PD* controller. The output relation of the fuzzy *PD* controller can be used in designing a fuzzy *PID* controller. Let an integrator be connected serially with a portion of the output of the fuzzy *PD* controller as shown in Fig. (6). The structure of the proposed fuzzy controller is simply connected the fuzzy *PD* controller together in parallel with an integrator. The output of the controller can be approximated by

$$u'_{EAF} = \alpha u_{EAF} + \beta \int u_{EAF}\, dt \tag{27}$$

Symbol α and β are the weight on the fuzzy *PD* and *PI* controller as defined before. The values of α and β are chosen in our study case as 5.0 and 1.0 respectively.

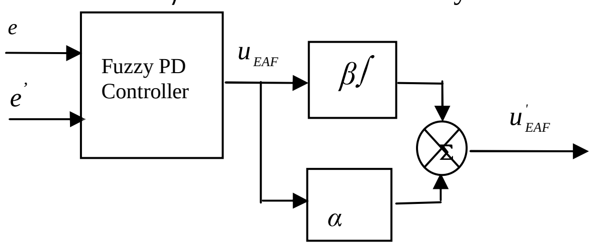

Fig.(7) PID controller I/O description

6. Simulation Results to 10% Disturbance in the Impedance of the Raw Material

Standard ferrosilicon arc furnace was used for this study. The numerical values for the raw material used in this study are given in Table [A.1] and Table [A.2] in appendix A. For comparison, simulations with the proposed fuzzy *PID* controller and the conventional *PID* controller were run.

Figure (8) shows a 10% disturbance in the impedance of electrode 1. The response shows a value of impedance equal to 2.44 mΩ then due to disturbance it goes down to 2.23 mΩ. The drop in impedance means a significant change in the temperature of the furnace. The conventional *PID* controller raises the value to 2.44 mΩ with higher overshoot, while the fuzzy *PID* controller raises gradually the value of impedance to 2.44 mΩ with lower overshoot and fast settling time. Lower overshoot in the three phase submerged arc ferrosilicon furnace gives the benefit of no hazard in the transformer circuit due to the lower impedance. Figure (9) shows the corresponding current response 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 63.0 KA. With conventional *PID* it reaches 58 KA with higher overshoot while with fuzzy *PID* it reaches 58 KA with lower overshoot and fast settling time. Same results are obtained for electrodes two and three as shown in Figs. (10-13). 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.

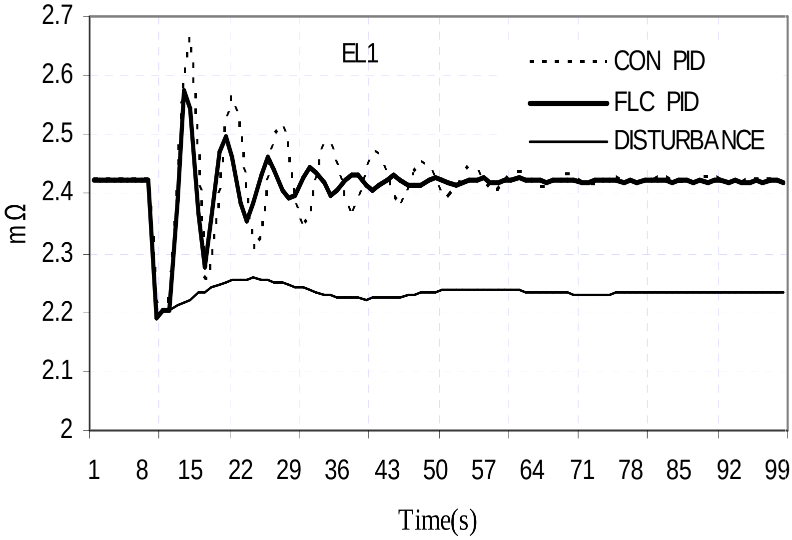

Fig. (8) Impedance responses of electrode 1

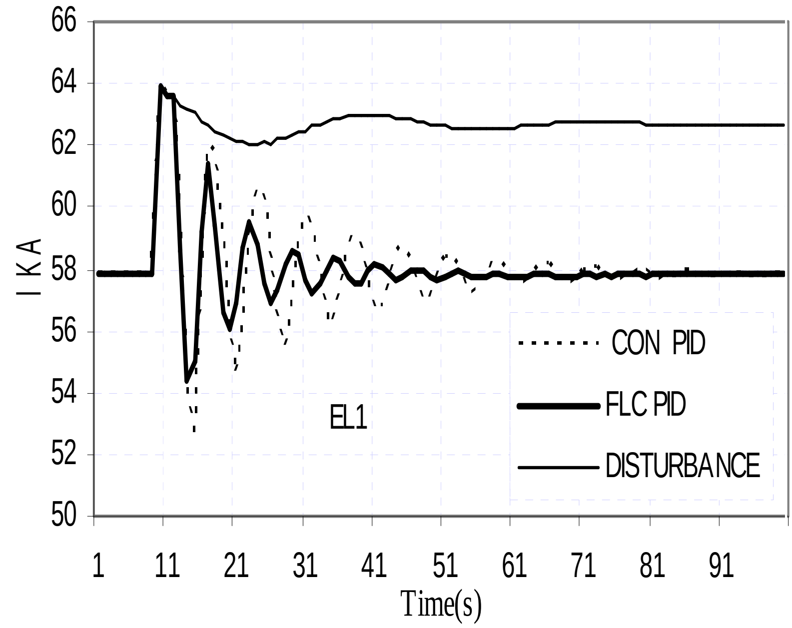

Fig. (9) Current responses of electrode1

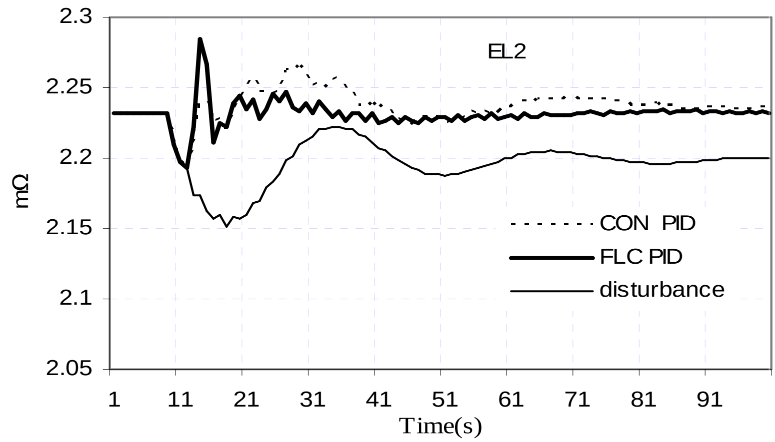

Fig. (10) Impedance responses of electrode 2

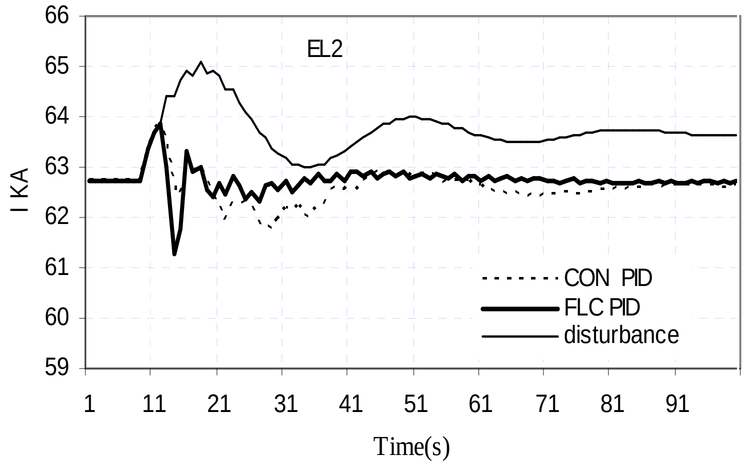

Fig. (11) Current responses of electrode2

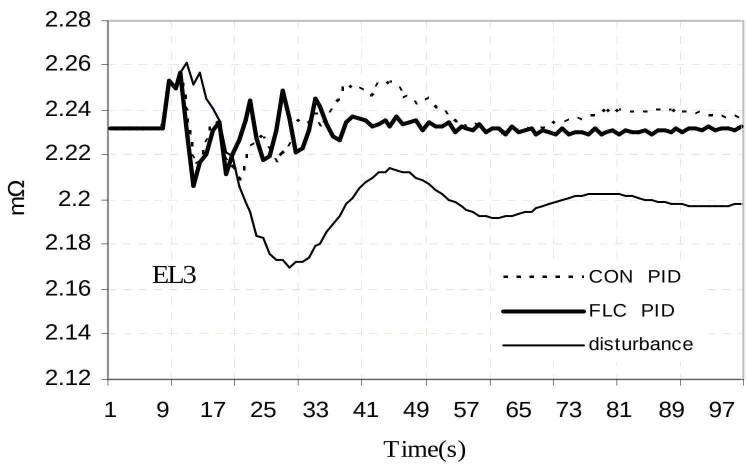

Fig. (12) Impedance responses of electrode 3

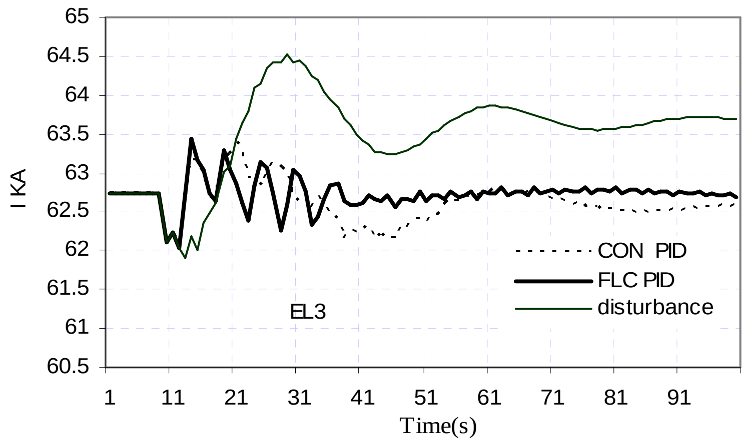

Fig. (13) Current responses of electrode3

7. CONCLUSIONS

The following conclusions can be drawn from the application of fuzzy logic to the control of arc ferrosilicon furnace as described in this paper:

a. Some aspects concerning the modeling and fuzzy logic control of the conductances and currents of the electrodes in an electrical arc furnace were presented.
b. The model forming a submerged arc ferrosilicon furnace was successfully solved using C++ language program. When the study of the proposed fuzzy *PID* controller is compared with the conventional *PID* controller, the results obtained show that the performance of the proposed fuzzy *PID* controller might be more successful when the parameters α and β are well adjusted.
c. The steady state error resulted from using fuzzy *PD* controller in [23] is mainly eliminated using the proposed fuzzy *PID* controller.
d. The proposed fuzzy *PID* controller declares a better damping and settling time which improves the EAF system performance.
e. Fuzzy logic control is a promising control technique and would be effectively used for improved process control of arc ferrosilicon furnace.
f. The study will continue to increase the effectiveness of the proposed fuzzy *PID* controller by adding the adaptive property to it.

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APPENDIX A: NUMERICAL DATA FOR SUBMERGED ARC FERROSILICON FURNACE

Table [A.1] shows the numerical values for the raw material, while Table [A.2] shows the numerical values for the walls of the ferrosilicon arc furnace.

Table [A.1] Numerical values of the components of the arc ferrosilicon furnace

Material	Density ton/m^3	Specific heat Mkal/ton.deg
Quartz	1.7	1.68
Coke	0.53	0.2
Fe_2O_3	2.3	0.11
Average due to mass	1.44325	1.09804

Table [A.2] Numerical values of the components of the walls of the arc ferrosilicon furnace

Property of walls	Numerical value
Walls density ton/m^3 ρ_w	2.5
Walls specific heat MCal/ton.deg C_w	0.3
Walls heat transfer coefficient Mkal/m^2.h.deg h_w	0.2
Walls volume m^3 V_w	48.3693
Walls surface m^2 S_w	57.776
Heat transfer coefficient between sphere and wall Mkal/m^2.h.deg	0.2

The constants T_1, T_2, K_1, K_2 and K of Eq. (9) can be calculated using the parameters of the heat transfer model and are found as follows:

$T_1 = 6.375287$ hour

$T_2 = 1.29634$ hour

$K_1 = 0.0970692$

$K_2 = 1.0$

$K = 0.0643376$

The parameters of the *PID* controller are chosen as follows:

$K_P = 1.2,\ K_I = 1.0,\ K_D = 0.169375$

The parameters of the fuzzy *PID* controller are chosen as follows:

$\alpha = 5.0,\ \beta = 1.0$

نمذجة ومحاكاة الحاكمات اللامحدودة ثلاثية البارامترات لأفران الفيروسيلكون ذات الأقواس المغمورة

فى هذا البحث تم دراسة وضع استراتيجية تحكم فى الطاقة الكهربية الداخلة لأفران الفيروسيلكون ثلاثية الأطوار. يوجد دخلين فى نظم التحكم اللامحدود التقليدي وهما إشارة الخطأ فى التوصيلية وكذلك معدل إشارة الخطأ فيها. عند مقارنة خرج الحاكمات اللامحدودة التقليدية مع النوع التناسبى التفاضلى التقليدى وجد انه يحتاج إلى إعادة دقة فى حالة الاستقرار. لإعادة ضبط الحاكم اللامحدود التقليدى لابد من استخدام الحاكم اللامحدود من نوع ثلاثى البارامترات الذى يتميز بأنه حاكم لاخطى. يهتم هذا البحث فى إدخال خاصية التكامل للحاكم اللامحدود التقليدى. ونتيجة إدخال هذه الخاصية هي الحصول على حاكم لا محدود يشبه الحاكم ثلاثى البارامترات التقليدى ولكنه متغير البارامترات. فى هذا البحث تم تمثيل فرن الفيروسيلكون بنظام انتقال حرارة، النظام الكهربى، وكذلك ديناميكية وضع الأقطاب وقد تم اختبار الحاكم المقترح عن طريق المحاكاة على فرن الفيروسيلكون باستخدام برنامج بلغة C++ وكانت النتائج التى حصلنا عليها جيدة مقارنة باستخدام الحاكمات التقليدية ثلاثية البارامترات بمفردها