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Comparison between classic PID, Integer Order PID and Fuzzy Logic Controller for Ceramic Infrared Heater: Analysis using MATLAB/Simulink

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Abstract*— This paper discusses the design, simulation and performance of ceramic infrared heater controller. This heater is energy saving potential, efficient heat transfer, uniform heating, efficient and instant heat. Many industries are increasibily making use of infrared technology as a means of improving their process. This type of heating often requires a large area of floor space. This study successfully developed a controller to achieve an effective and robust control of the infrared heating process. This paper consists three main tuning methods for IR heating system controller. Firstly, it presents design of PID controller using Zeigler Nichols (ZN) technique for first order plus time delay system using open loop step response method. Secondly, it presents the design of PID controller based on gain margin and phase margin (IOPID) for the same system. Thirdly, a fuzzy logic controller used for the same system for good stability and robust performance. Performance analysis shows the effectiveness of the ZN-PID, IOPID and fuzzy logic controller.

Index Terms*— Zeigler Nichols, PID, IOPID, Gain margin, Phase margin, Fuzzy Logic

I. Introduction

Conventional PID controller operates the majority of the control system in the world due to simple in algorithm, good in stability, high in reliability, easy in design and wide in adaption. The PID controller is used in wide range of problems like automotive, instrumentation, motor drives etc. PID controller provides robust and reliable performance for most of the systems if the PID parameters are tuned properly. Among these tuning methods the Zeigler Nichols (ZN) technique has been very influential. Zeigler Nichols presents two tuning methods, a step response method and ultimate frequency response method. In this paper we will investigate step response method for the IR heating controller.

In order to solve the problem, a control method which uses IOPID method based on gain and phase margin specification in temperature control for IR heating system is proposed in this paper. On the basis of gain and phase margin, IOPID controller can make entire use of the successful operations.

The field of fuzzy control has been making rapid progress in recent years .Fuzzy logic controller has been widely used for non-linear, time delay and high order system. The tuning of the parameters of the fuzzy module can be easily done by computational efforts. The methodology is shown to be effective for a higher static gain. In this paper, a novel methodology used based on the fuzzification. In this the value of the proportional gain is multiplied by a constant parameter less than one to reduce the overshoot, but has the drawback of increasing the rise time. To achieve both the aims of reducing the overshoot and decreasing the rise time, a fuzzy module depending upon the current output error and its derivative are used.

II. PID Tuning

The PID controller has the following standard form in the time domain [3]

$$C(t) = K_p \left[e(t) + T_d \frac{d}{dt} e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau \right] \quad (1)$$

where

$e(t)$ = system error;

K_p =Proportional gain;

T_d =Derivative gain constant;

T_i =Integral time constant;

We can also write equation (1) as

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$$C(t) = K_p e(t) + K_d \frac{d}{dt} e(t) + K_i \int_0^t e(\tau) d\tau$$

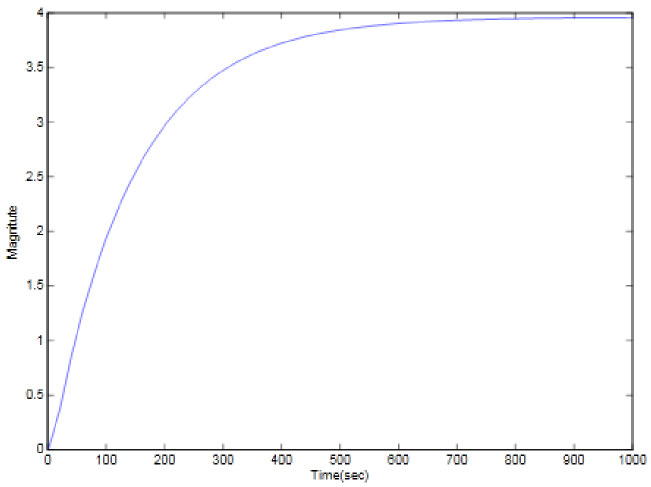
(2)

Where it is obviously $K_d = K_p T_d$ or $K_i = K_p / T_i$

The transfer function of PID controller is given as

$$C(s) = K_p + \frac{K_i}{s} + K_d \qquad (3)$$

Zeigler Nichols step response method is based on transient response experiment. The open loop step response of the IR heater under test resulted in the curve [1], [2] is shown in fig (1)



Fig(1): Mat Lab output of step response of IR heater Plant

The step response of IR heater is compared with the unit step response of a typical industrial process shown in fig (2) to determine the parameters of the process [3], [4].

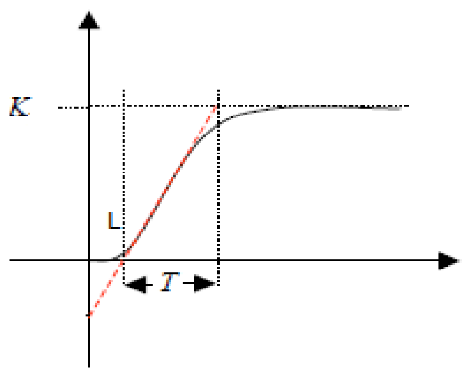


Fig (2): Step response with plant

From fig (2), the plant transfer function represented as

$$P(s) = \frac{K}{1 + sT} e^{-sL}$$

(4)

Where K is the static gain, L is the time delay and T is the time constant

By comparing fig (1) and fig (2) the transfer function represented as

$$P(s) = \frac{3.96}{140s + 1} e^{-7s}$$

(5)

Using the Zeigler – Nichols step response method formula in the table (1)

TABLE I: Tuning formula for ZN-PID

PID Controller	$K_{p} = \frac{1.2}{K}\left(\frac{T}{L}\right)$	$K_i = 2L$	$K_d = 0.5L$

From the general form for PID controller in equation (3)

$$C_{ZNPID}(s) = 6.06 + \frac{0.432}{s} + 21.21s \qquad (6)$$

III. Design of Integer Order PID Controller

The open loop transfer function G(s) is

G(s) =C(s) P(s)

According to the first order plus time delay system transfer function P(s) we get its frequency response as

$$P(j\omega) = \frac{K}{jT\omega + 1} e^{-jL\omega}$$

$$= \frac{K}{\sqrt{1 + \omega^2 T^2}} e^{-(\tan^{-1}(\omega T) + L\omega)}$$

The gain and phase of the plant are as follow

$$|P(j\omega)| = \frac{K}{\sqrt{1 + \omega^2 T^2}}$$

(7)

$$Arg[P(j\omega)] = -\tan^{-1}(\omega T) - L\omega \qquad (8)$$

A. Design Specification

The objective of this paper is to design a fractional order controller so that the system fulfills different specifications regarding to the plant uncertainties, load disturbance and high frequency noise. Therefore, the design problem is formulated as follows [5],[10].

i. Phase Margin and Gain crossover frequency specification

Gain and phase margin have always served important parameter for robustness. It is known that the phase margin is related to the damping of

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the system. The equations that define the phase margin ϕ_{pm} and gain crossover frequency ω_{cp} are

$$\left|G(j\omega_{cp})\right| = \left|C(j\omega_{cp})P(j\omega_{cp})\right|_{dB} = 0dB$$

(9)

$$Arg[G(j\omega_{cp})] = Arg[C(j\omega_{cp})P(j\omega_{cp})] = -\pi + \phi_{pm} \qquad (10)$$

ii. Robustness to gain variation in the gain of the plant

The gain variation of the plant demands that the phase directives w.r.t the frequency is zero, i.e. the phase bode plot is flat, at the gain crossover frequency.

$$\left(\frac{d(Arg(G(j\omega))}{d\omega}\right)_{\omega=\omega_{cp}} = 0 \qquad (11)$$

B. Integer Order PID Controller Design

The open loop transfer function $G_1(s)$ for the IOPID with FOPTD system is given as

$$G_1(s) = C(s)P(s) \qquad (12)$$

According to the IOPID controller transfer function (7), we can get the frequency response as,

$$C(j\omega) = K_p + \frac{K_i}{j\omega} + j\omega K_d$$

The gain and phase are as follow,

$$\left|C(j\omega)\right| = \sqrt{K_p^{\,2} + (K_d\omega - (K_i/(\omega K_p))^2}$$

(13)

$$Arg[C(j\omega)] = \tan^{-1}((K_d\omega^2 - K_i)/(\omega K_p))$$

(14)

Then the open loop frequency response

$$G_1(j\omega) = C(j\omega)P(j\omega)$$

The gain and phase of the open loop frequency response are as follows by using (5), (13) and (14)

$$\left|G_1(j\omega)\right| = \left|C(j\omega)\right|\left|P(j\omega)\right| = \frac{K\sqrt{K_p^{\,2} + (K_d\omega - (K_i/(\omega K_p))^2}}{\sqrt{1+\omega^2T^2}} \qquad (15)$$

$$Arg[G_1(j\omega)] = \tan^{-1}((K_d\omega^2 - K_i)/(\omega K_p)) - \tan^{-1}(\omega T) - L\omega \qquad (16)$$

According to specification (i), the phase of $G_1(j\omega)$ can be expressed as in as a form of ω_{cp} is

$$Arg[G_1(j\omega_{cp})] = \tan^{-1}((K_d\omega_{cp}^{\,2} - K_i)/(\omega_{cp}K_p)) - \tan^{-1}(\omega_{cp}T) - L\omega_{cp}$$

$$= -\pi + \phi_{pm} \qquad (17)$$

Then,

$$\frac{K_d\omega^2_{cp} - K_i}{K_p\omega_{cp}} = A_1$$

Where $A_1 = \tan\left[\tan^{-1}(\omega_{cp}T) + L\omega_{cp} + \phi_{pm}\right]$

And according to specification (ii) about the robustness to gain variation in the plant,

$$\left(\frac{d(Arg(G_1(j\omega))}{d\omega}\right)_{\omega=\omega_{cp}} = 0$$

So

$$= \frac{d}{d\omega}\left(\tan^{-1}((K_d\omega_{cp}^{\,2} - K_i)/(\omega_{cp}K_p)) - \tan^{-1}(\omega_{cp}T) - L\omega_c\right)_{\omega=\omega_{cp}} = 0 \qquad (18)$$

Then we get,

$$\frac{K_p(\omega_{cp}^{\,2}K_d + K_i)}{\omega_{cp}^{\,2}K_p^{\,2} + (K_d\omega_{cp}^{\,2} - K_i)} = \frac{T}{1+\omega_{cp}^{\,2}T^2} + L$$

Where

$$1 + \omega_{cp}^{\,2}T^2 = B_1$$

According to the specification (ii), we established an equation about K_p,

$$\left|G_1(j\omega_{cp})\right| = \left|C_1(j\omega_{cp})\right|\left|P(j\omega_{cp})\right|$$

$$= \frac{\sqrt{K_p^{\,2} + (K_d\omega_{cp} - (K_i/(\omega_{cp}K_p))^2}}{\sqrt{1+\omega_{cp}^{\,2}T^2}} = 1$$

(19)

From (17) (18) and (19), we can get

$$K_p = \frac{1}{k}\sqrt{\frac{B_1}{1+A_1^2}}$$

$$K_i = \frac{1}{2k}\left[\sqrt{\frac{1+A_1^2}{B_1}}(T\omega_{cp} + LB_1\omega_{cp}^{\,2}) - A_1\omega_{cp}\sqrt{\frac{B_1}{1+A_1^2}}\right]$$

$$K_d = \frac{1}{2k}\left[\sqrt{\frac{1+A_1^2}{B_1}}(T + LB_1) - A_1\omega_{cp}^{\,-1}\sqrt{\frac{B_1}{1+A_1^2}}\right]$$

If the parameter are set as follows

ω_{cp} =0.08 rad/sec, T=140sec, L=7sec, $\phi_{pm} = 60^\circ$

Then we get K_p, K_i and K_d directly

K_p =2.825, K_i =0.0855 and K_d =9.74

Let IOPID controller obtained from C_{IOPID} as

$$C_{IOPID} = 2.825 + \frac{0.0855}{s} + 9.74s \qquad (20)$$

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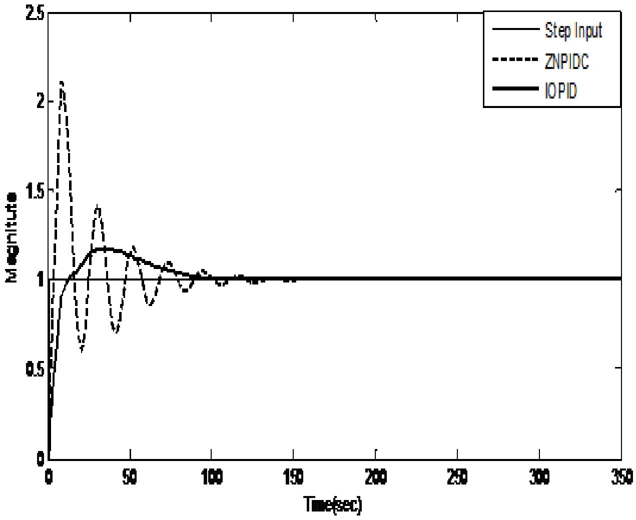
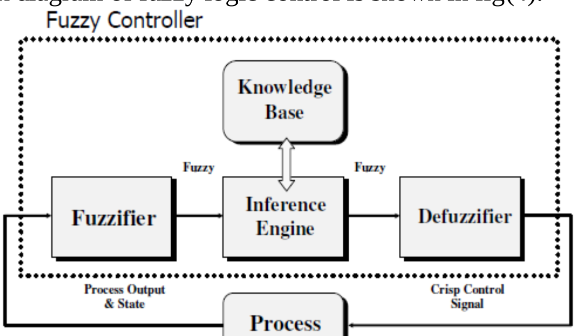


Fig(3):- Step response of the system with ZNPIDC and IOPID

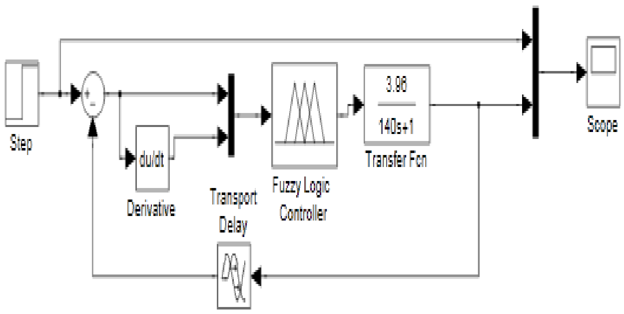
IV. Fuzzy Logic Controller

Fuzzy logic control is based on fuzzy set theory, linguistic variable and fuzzy inference. Due to this fuzzy logic control is also been known as intelligent control[13] ,[14]. The basic block diagram of fuzzy logic control is shown in fig(4).



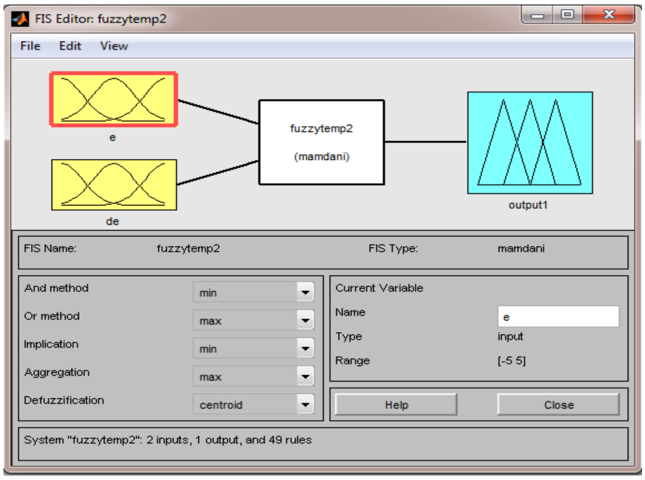
Fig(4):-Basic block diagram of fuzzy logic controller

In order to verify the effectiveness of the fuzzy logic controller and compare the control performance with the conventional PID controller and IOPID, we make a simulation with the below simplified model shown in fig(5) using Mat Lab simulink.



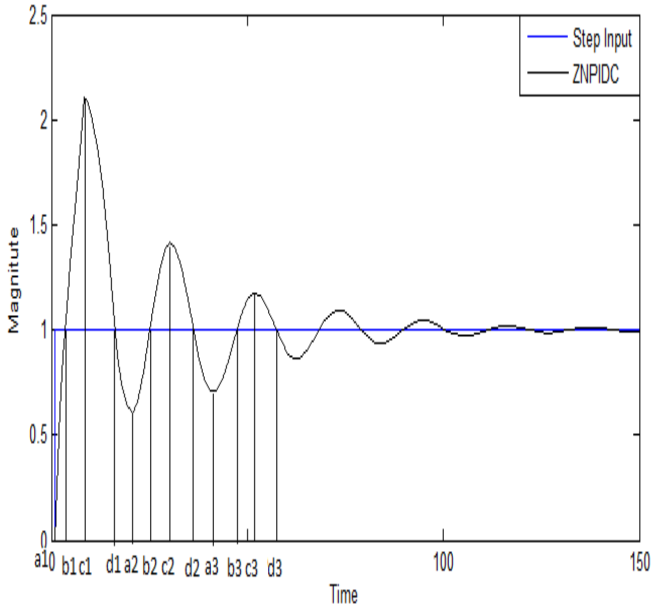
Fig(5):-Implementation of fuzzy logic controller with plant using simulink

For a two input fuzzy logic controller 3,5,7,9 or 11 membership function for each input are mostly uses. In this paper, only seven fuzzy membership function are used for two input error (e) and derivative error (de) and the fuzzy membership functions for the output parameter are shown in fig (6), here NB means negative big, NM means negative medium, NS means negative small, ZO means zero, PS means positive small, PM means positive medium and PB means positive big.



Fig(6): membership function editor for fuzzy controller

The fuzzy linguistic rules are defined from output response of the system using ZNPID controller as shown in fig(7)



Fig(7): Output response of plant with ZNPID controller for observation of deriving fuzzy control rules

This FLC design is quite intuitive and transparent to the users[15]. The rule base applies the appropriate control action depending on how far the response is moving towards the set point (i.e. error and derivative error).

Fig(7) illustrates the effectiveness of having direct control over the error and change of error in driving the temperature to a prescribed set point.

Table II :- Prototype of fuzzy control rules with term sets

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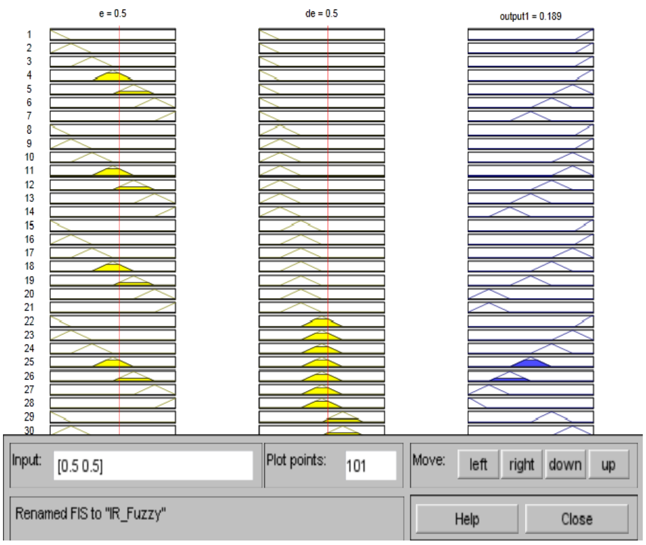
Rule No.	e	de	du	Reference Point
1	PB	ZO	PB	a1
2	PM	ZO	PM	a 2
3	PS	ZO	PS	a 3
4	ZO	NB	NB	b 1
5	ZO	NM	NM	b 2
6	ZO	NS	NS	b 3
7	NB	ZO	NB	c 1
8	NM	ZO	NM	c 2
9	NS	ZO	NS	c 3
10	ZO	PB	PB	d 1
11	ZO	PM	PM	d 2
12	ZO	PS	PS	d 3
13	ZO	ZO	ZO	set point

The system response divided into seven phase. Depending upon the output is increasing or decreasing, 49 rules are been divided for the fuzzy logic controller shown in table (3).These 49 rules are sufficient to cover all possible situation for high static gain first order plus time delay system.

Table III: Rules base for fuzzy logic controller

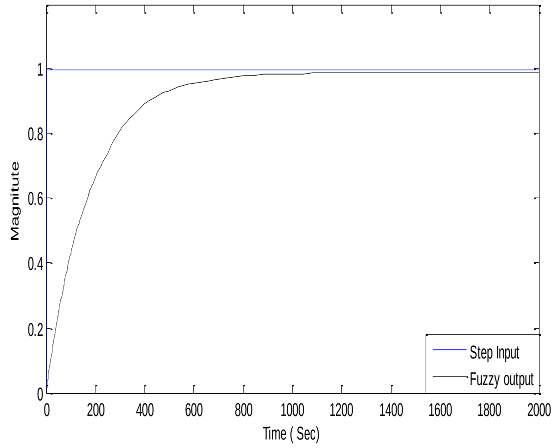
de \ e	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	ZO
NM	PB	PB	PM	PM	PS	ZO	NS
NS	PB	PB	PM	PS	ZO	NM	NM
ZO	PB	PM	PS	ZO	NS	NM	NB
PS	PS	PM	ZO	NS	NM	NB	NB
PM	PS	ZO	NS	NM	NM	NB	NB
PB	ZO	NS	NM	NB	NB	NB	NB



Fig(8):-Rule viewer for fuzzy logic controller

The Rule Viewer displays a roadmap of the whole fuzzy inference process and shows one calculation at a time. In this sense, it presents a sort of micro view of the fuzzy inference system.

Step response of the fuzzy logic based controlled first high order static gain first order plus time delay process is shown below



Fig(9): step response of fuzzy logic controller

V. Conclusion

This paper presented the design of PID controller using open loop step response method, Inter order PID controller based on gain margin and phase margin and fuzzy logic controller for high static gain based first order plus time delay system.

Simulation results using MatLab/Simulink are discussed for ZN tuned PID, IOPID and the Fuzzy logic controller. The Design is carried out in MATLAB and has been observed that the system response is improved after implementing fuzzy logic controller. The proposed methodology gives better performance in the rise time, peak overshoot and the steady state error. The responses observed from the IOPID controller have a slight over shoot which can be further improved by implementing fuzzy logic controller. But it is observed that, from the simulation that the fuzzy logic controller performs better response than IOPID controller and conventional PID controller.

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