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An application of Nonlinear Fuzzy PID Controller for Performance improvement in a temperature control process

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ABSTRACT: *PID controllers have found wide application in process control of time delay systems. The classical control methods designed with conventional PID controllers usually result in overshoot, significant reaction and stabilizing times in regards to optimal performance requirements. In this paper we have proposed the application of nonlinear fuzzy PID controller as an intelligent controller, in the temperature control process of a laboratory oven. The process of temperature control is modelled as a first order plus time delay (FOPDT) process. The performance of the proposed control system with nonlinear fuzzy PID algorithm is analyzed through the step response characteristics, and comparison of the proposed approach with the cases when classical PID controllers are applied, is also provided. From the obtained results, we conclude that the nonlinear fuzzy PID controller achieves better control performance in time delay processes comparing to the classical methods.*

Keywords: *nonlinear fuzzy, PID, time delay*

I. INTRODUCTION

Delays are frequently faced in control systems as computing or processing delays or as delays imposed by information transmission [1]. Time delays are common in industrial processes which are characterized by energy and materials transport, such as chemical, biological, information, measuring, computing processes, etc. Time delays introduce problems in process control due to decrease of robustness and performance deterioration, which brings the systems close to instability [1]. To achieve the control of such processes, PID controllers have found wide application [2]. Given that approximately 95% of the control schemes in practice are built on PID controllers, finding the right parameters that improve at maximum the control performance, poses a challenge in itself [3]. Their popularity is related to the fact that they are simple to understand and to operate by operators, and are effective and robust in control [4].

There exists many methods for the calculation of the PID optimal parameters, in order to obtain a specific characteristic of process time response [5]. To check the effectiveness of various design methods for PID controllers, the comparison is made by analyzing the transient characteristics of the system. The characteristics obtained by adjusting the PID parameters, often do not meet the control performance criteria defined by the designer. For this reason, methods based on intelligent nonlinear control algorithms, are introduced which result very efficient in improving the overall control performance of time delay systems.

Nonlinear fuzzy PID controllers [6] are derivations of the basic fuzzy linear controllers which are based on the PID coefficients to define the fuzzy gain parameters. The application of the nonlinear fuzzy PID controller in the control of a time delay process is the main focus of this work. Transient response performance criteria such as rising time, settling time, overshoot, peak value, peak time are used to perform the performance comparison between classical PID control and proposed nonlinear fuzzy PID control of the temperature control process.

The structure of the article is as follows. Section II presents the classical PID control for the temperature control process, modelled as a first order time delay process and also the transient response performance criteria, that will be used as the basis for comparison between the two control approaches. Section III presents the proposed control approach with nonlinear fuzzy PID controller. All performed simulations and achieved results with classical method (PID controller) and intelligent method (nonlinear fuzzy PID) are presented in section IV. Conclusions obtained from simulations are presented in section V. Algorithms and computational simulations are performed in Matlab R2015b environment.

II. PROBLEM FORMULATION

The application of classical PID controller in parallel form in a closed loop is illustrated in Fig.1.

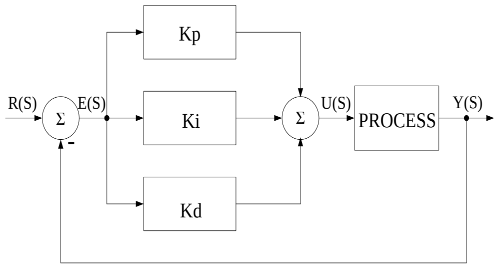

Fig.1 Structure of PID controller

Signals presented in the control scheme are:
R(s)-reference signal. In our case, a step function is taken as reference.
Y(s)-output signal of the system
U(s)-control signal
E(s)-error signal, derived from *E(s)=R(s)-Y(s)*
Proposed PID controller is in its parallel form, and is provided by the algorithm:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt}e(t) \quad (1)$$

Where
u(t)-control signal in time domain
K_p-proportional coefficient, a tuning parameter
K_i- integral coefficient, a tuning parameter
K_d- derivative coefficient, a tuning parameter
e(t)-error signal in time domain
Some very popular classical methods for design of PID controllers are used to have a first view of the difficulties faced with the control of time delay systems.
The Ziegler-Nichols (ZN) tuning formula [7] is obtained when the plant model is given by a first order plus dead time model (2).

$$G(s) = \frac{k}{Ts+1}e^{-Ls} \quad (2)$$

Where k, T, L are respectively amplification gain, time constant and time delay of the process. Based on process step response, PID controller coefficients with Ziegler-Nichols design method are defined as in (3):

$$a = kL/T$$
$$K_p = 1.2/a$$
$$T_i = 2L$$
$$T_d = L/2 \quad (3)$$

Where T_i is the time constant of the integral term and T_d is the time constant of the derivative term.
Chien-Hrones-Reswick (CHR) design method [8] is also based on first order plus dead time model of the process.The CHR method uses the time constant *T* of the process explicitly as is illustrated in the tuning formulas (4) and (5). For setpoint regulation, CHR proposed two tuning methods, with 0% overshoot and 20% overshoot.
For 0% overshoot:

$$a = kL/T,\ K_p = 0.6/a,\ T_i = T,\ T_d = 0.5L \quad (4)$$

For 20% overshoot:

$$a = kL/T,\ K_p = 0.95/a,\ T_i = 1.4T,\ T_d = 0.47L \quad (5)$$

Cohen-Coon (CC) design method [9] is based on first order plus dead time model of the process. The tuning formulas for the PID coefficients are listed in relations (6).

$$a = kL/T,\ \tau = L/(L+T),\ K_p = \frac{1.35}{a}\left(1 + \frac{0.18\tau}{1-\tau}\right),\ T_i = \frac{2.5-2\tau}{1-0.39\tau}L,\ T_d = \frac{0.37-0.37\tau}{1-0.81\tau}L \quad (6)$$

Wang, Juang, and Chan (WJC) design method [10] is based on ITAE performance criterion. The tuning formulas for the PID coefficients are listed in relations (7).

$$K_p = \frac{(0.7303+0.5307T/L)(T+0.5L)}{K(T+L)},\ T_i = T + 0.5L,\ T_d = \frac{0.5LT}{T+0.5L} \quad (7)$$

The process that is studied is a single input-single output first order system with time delay, which represents many processes in industry. The first order plus time delay model is retrieved from the process identification procedure of the temperature control process of a laboratory oven model G34/EV. The experiment set is shown in Fig.2. Based on the surface method applied in this case for the open loop step response, the identified transfer function of the temperature control process is:

$$G(s) = \frac{1.33}{1400s+1}e^{-30s} \quad (8)$$

This is a self-regulating process with rising time $t_r = 1281$ seconds and settling time $t_s = 2307$ seconds.

The delay term e^{-Ls}, according to [2], can be approximated by a rational transfer function of the Pade form of n-th order:

$$e^{-s} \approx \frac{\sum_{i=0}^{n}\binom{n}{i}\frac{(2n-i)!}{(2n)!}(-s)^i}{\sum_{i=0}^{n}\binom{n}{i}\frac{(2n-i)!}{(2n)!}s^i} = \frac{\sum_{i=0}^{n}\frac{(2n-i)!n!}{(2n)!(n-1)!i!}(-s)^i}{\sum_{i=0}^{n}\frac{(2n-i)!n!}{(2n)!(n-1)!i!}s^i} \quad (9)$$

In our case, in order to design the fuzzy nonlinear PID controllers a second order model approximation of time delay is performed. The rational approximated model obtained for the temperature control process is:

$$G_{pade,2}(s) = \frac{1.33s^2 - 0.266s + 0.01773}{1400s^3 + 281s^2 + 18.87s + 0.0133} \quad (10)$$

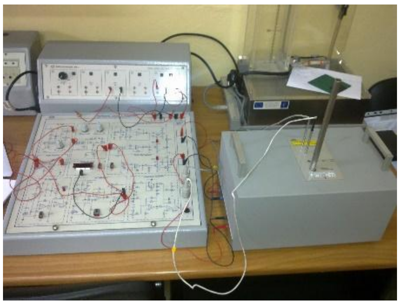

Fig.2 Experiment set for temperature control of laboratory oven

Analysis for the process transient response in time domain is performed through performance criteria [11] like:
-*Rising time* t_r: time required for the output of the system to reach 90% of its final value $h(\infty)$.
-*Settling time* t_s:time after which the output remains within ±2% of the final value $h(\infty)$
-*Overshoot* $M_r(\%)$: shows the peak overshoot value above the step value, expressed in percentage, which should preferrably be 1.2 (20%) or less.
-*Peak value* h_{max} :peak value of the transient response $h(t)$ of the process
-*Peak time* t_{peak}: time required for the transient response $h(t)$ to reach the peak value h_{max}
Rising and stabilizing time are measures of response speed of the system while overshoot, peak value, and settling time are measures related to the quality of response.

III. NONLINEAR FUZZY PID CONTROLLER

When the process is of order higher than two, the conventional PID controller starts to experience difficulties and better responses can be achieved with more complex controllers. Fuzzy Logic on which is based the proposed intelligent controller, follows an engineering treatment of the human knowledge and expertise, for the modelling and control of systems with nonlinearity and uncertainty. Almost all systems in industry are presented to nonlinearities and uncertainties due to inaccuracies in their measurements, modeling and control. Fuzzy controllers are designed on the linguistic rules of '*if-then*' form, which introduce the reasoning of these controllers similar to that of humans. Controlled variables can be combined in '*if-then*' rules by the connectives '*and*' and '*or*'. The proposed controller in our case is a nonlinear fuzzy PID controller which has a nonlinear control surface and structure similar to PID controller. The logical diagram of the main components of the proposed nonlinear fuzzy PID controller is presented in Fig.3. Inputs to the fuzzy inference system, are the crisp values of the controlled variables, that usually are *error E* and *change in error ΔE* of the control system. Fuzzification interface performs the lookup in the membership functions to derive the membership grades. It evaluates the input crisp measurements according to the rules premises. Each premise produces a membership grade expressing the degree of fulfilment of the premise. Knowledge base is the database which contains all designed control rules. The control rules are usually defined by control engineering experience and knowledge. The processing unit combines the membership values on the premise part, usually by multiplication action, to calculate the weights for each rule. Based on the weights of each rule, the fuzzy qualified output is then processed in the defuzzification interface. The defuzzification interface converts the fuzzy set μ_c, resulting from inference, to a single crisp number in order to form the control signal U to the plant.

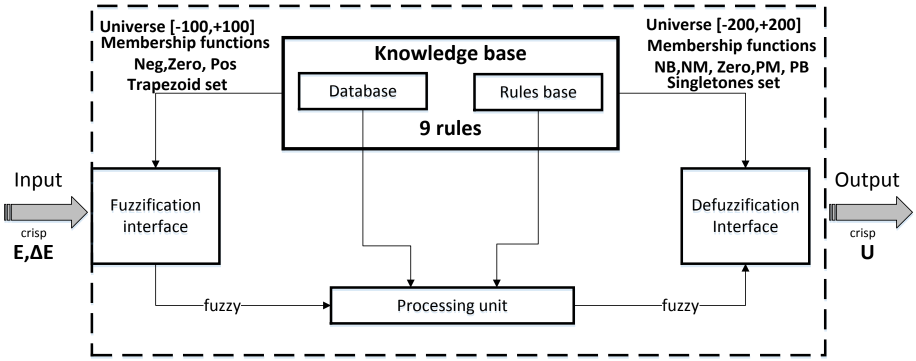

Fig.3 Fuzzy inference system

The sources of nonlinearity in fuzzy controllers are the position, shape and number of membership functions on the premise side. The proposed nonlinear fuzzy PID controller is composed of a fuzzy PD sub-controller and a separated integral action of the controller, as illustrated in Fig.4.

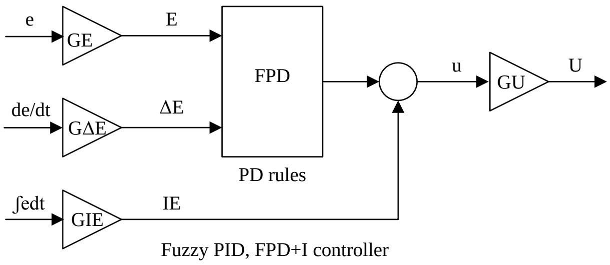

Fig.4 Nonlinear Fuzzy PID controller

A Sugeno inference system is proposed in this study. The amplification gains GU, $G\Delta E$, GIE of the nonlinear fuzzy PID controller are calculated based on the conventional PID controller coefficients, using the relations (11).

$$GU = \frac{K_P}{GE}, \quad G\Delta E = GE \cdot T_d, \quad GIE = GE \cdot 1/T_i \qquad (11)$$

Where K_p-proportional coefficient, T_i- integral time constant, T_d- derivative time constant
Two inputs, E , ΔE are selected, and the rule base will consist of nine rules. The premise universes are chosen as percentages of full scale of measurements *[-100,100]*. On the premise side, we have selected '*Neg*', '*Zero*' and '*Pos*' membership functions, meaning '*negative*', '*zero*' and '*positive*' values respectively, and on the conclusion side, we have selected '*NB*', '*NM*', '*Zero*', '*PM*' and '*PB*' membership functions, meaning '*negative big*', '*negative medium*', '*zero*', '*positive medium*', and '*positive big*', respectively. In order to achieve a nonlinear controller, membership functions on the premise side are selected as trapezoidal sets. The conclusion universe is in the range *[-200,200]* since there are two inputs, and the membership functions are singletons at $NB = -200$, $PB = 200$.
The premise variables '*error*' and '*change in error*' is combined with the connective '*and*', which is implemented as '*multiplication*' function. In this case, '*multiplication*' and '*sum*' functions are used for '*activation*' and for '*accumulation*' operations, respectively. The fuzzy control strategy, composed of nine rules, based on error and its derivative, is illustrated in Table 1 below:

Table 1 Rule base

Error E	Change in error ΔE	Output control signal u
Neg	Neg	NB
Neg	Zero	NM
Neg	Pos	Zero
Zero	Neg	NM
Zero	Zero	Zero
Zero	Pos	PM
Pos	Neg	Zero
Pos	Zero	PM
Pos	Pos	PB

Since, we have selected a Sugeno type controller, the output is a weighted average with the firing strength weighting the singletones positions. We have chosen $GE = 100$ since the error universe is *[-100,100]*, and the maximal error is *1*.

IV. SIMULATION RESULTS

Following the control design methods explained in sections II and III, simulations were run in Matlab software for the time delay process of temperature control. In the first part of simulations, the PID controllers based on the classical design methods were obtained. Closed loop step responses for the five classical PID designed methods were compared. Comparison of transient behaviors of the process for these 5 control methods is illustrated in Fig. 5

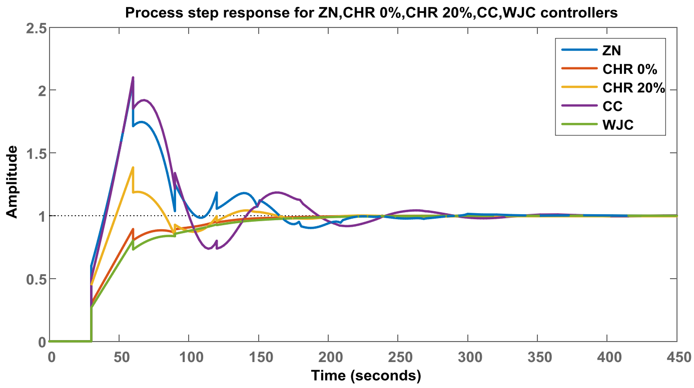

Fig. 5 Step responses of the temperature control process for the classical PID design methods

PID controller coefficients as well as performance criteria obtained from the simulations are included in Table 2.

Table 2. Obtained PID controllers coefficients and performance criteria with classical control design methods

PID design Method	Kp	Ti	Td	*Rising time* t_r	*Settling time* t_s	*Overshoot* $M_r(\%)$	*Peak value* h_{max}	*Peak time* t_{peak}
ZN	42.11	60	15	7.16	270.16	107.24	2.07	59.99
CHR 0%	21.05	1400	15	65.50	150.73	0	0.99	267.01
CHR 20%	33.33	1960	14.1	14.49	191.9	38.41	1.38	59.99
CC	47.55	74.35	11.06	8.47	278.8	110.10	2.10	59.99
WJC	18.97	1415	14.84	79.06	175.62	0	0.99	402.63

As seen from the results, the best performance is achieved with Chien-Hrones-Reswick (0% overshoot) and Wang-Juang-Chan methods.

The second part of simulations, include the design and simulation of the proposed intelligent nonlinear fuzzy PID controller. PID coefficients obtained from Chien-Hrones-Reswick (0% overshoot) method, were used as the basis for the calculation of the nonlinear fuzzy amplification gains. The resulting fuzzy amplification gains based on the relations (11) are:

$$GU = 0.2105\,, \quad G\Delta E = 1500\,, \quad GIE = 0.071 \qquad (12)$$

Input membership family applied in our case is illustrated in Fig. 6.

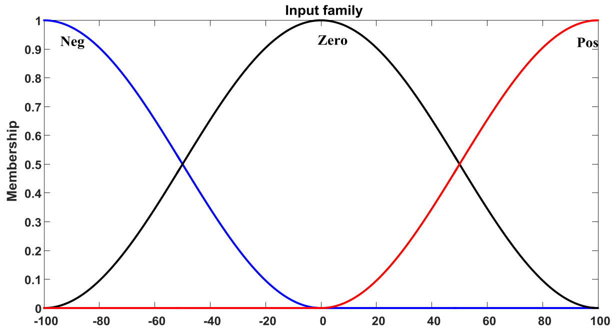

Fig.6 Input membership functions

The control surface for the proposed nonlinear fuzzy PID controller with a nine rules base, is illustrated in Fig. 7.

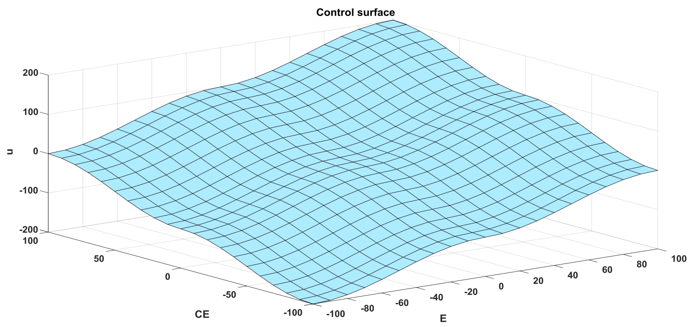

Fig. 7 Control surface of the nonlinear fuzzy PID controller

Step response of the temperature control process obtained with a nonlinear fuzzy PID controller is illustrated in Fig. 8.

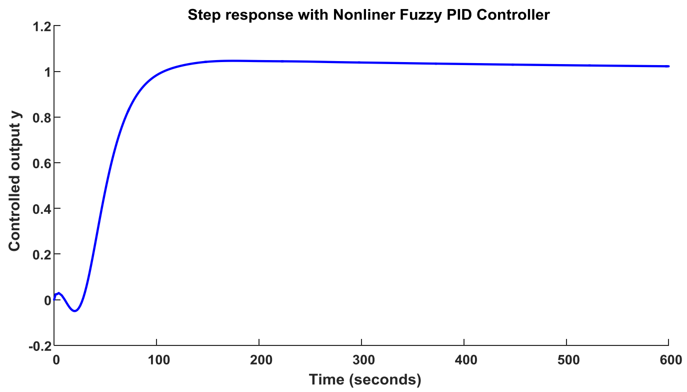

Fig. 8 Step response of the temperature control process for the nonlinear fuzzy PID controller case

The resulting performance criteria for the nonlinear fuzzy PID controller case are: rising time $t_r = 62$ seconds, settling time $t_s = 105$ seconds and overshot $M_r(\%)$ =2.3%.

V. CONCLUSION

From the simulations performed, we conclude that the proposed intelligent fuzzy nonlinear PID controller is very efficient in achieving a better control performance compared to classical PID controllers, for the temperature control process, which is a time delay process. Especially performance criteria achieved with this control method, like rising time and settling time are reduced approx. 20 times compared to the values of the process, and are lower than the best values achieved with CHR and WJC control methods. This indicates that the proposed control system with nonlinear fuzzy PID controller reacts quickly to the input disturbances of the system. The system behavior with nonlinear fuzzy PID controller has no oscillations, compared to the behavior achieved with the classical PID design methods.

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