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Application of Auto-Tuner Fuzzy PID Controller on Industrial Cascade Control

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Abstract: In this paper, the effectiveness of a newly proposed optimized cascade control technique, utilizing fuzzy control applied to a furnace temperature model is presented. PID controllers are widely used in the process industry due to its simplicity and robustness. To improve the control scheme, cascade control is the apparent choice due to its wide application in critical applications of the industry, such as heater temperature control, compressor capacity control, heat exchanger temperature control and fractionation columns controls. From the work done, it is observed that with changes to process transfer function, the proposed design has a better adaptation and performs better than the conventional cascade PID control. The proposed design utilizes Fuzzy Logic to continuously tune each term of the PID controller. The performance of the proposed design is evaluated with respect to the conventional cascade PID controller. To evaluate the performance of each controller, the system's stability and performance parameters such as rise time, overshoot, undershoot and settling time were determined. The entire system design is modelled using MATLAB/ SIMULINK, with the simulation results showing that the proposed fuzzy logic cascade controller has better robustness and dynamic performance than the conventional controller.

Keywords: Auto-tuning, Cascade Controll, Fuzzy Logic, PID-control, Simulink.

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1. INTRODUCTION

One of the best flexibility with PID controllers is the improvement of dynamic performance when utilizing two PIDs together. This is known as cascade PID controller [1]. In cascade controller, the two PIDs are placed in such a way that the set point of one PID is the output of the other PID, i.e. one of the PID controllers works as the inner loop controller which takes the output of the other PID controller which works as the outer controller as its remote set point [2].

PID controllers work well with a linear system. Typically, various processes are non-linear, hence frequent tuning of the parameters are required [3,8]. A non-linear condition comes from the changes in the process itself, performance of equipment, as well as wear and tear of the instrumentation. To manage this, the paper introduces an auto tuner fuzzy control for the PID terms that allow for better adaptive control, thus avoiding the need for frequent tuning. The application of Fuzzy PID in the industry has seen its applicability in {9] and [10]. In order to show the effectiveness of the proposed controller, a transfer function of a furnace temperature is utilized [4].

2. BACKGROUND

2.1 Furnace Control System

Furnaces are used in the oil and gas industry to provide the source for heat, using fuel combustion. The fuels used could be solid, liquid or gas based. The general feature of the furnaces is heat transfer from hot source to a cold sink. The design of the furnaces varies based on its function, heating duty, type of fuel and combustion air features. The furnaces are fired using burners, either single or multiple burners. Fuel flows into the burner and is burnt with air which is provided from a forced-draft fan or natural draft. The flames heat up the tubes, which in turn heat the fluid inside the furnace, in a radiant section known as firebox. In this chamber, continuous combustion takes place, with heat that is transferred mainly by radiation to tubes around the fire of the chamber. To control the required heat, the feed outlet temperature is controlled with the fuel pressure control as part of a cascade control scheme.

This paper will look into the control scheme improvement for a natural draft gas heater furnace, using natural gas as the fuel to heat up regeneration gas that is used to regenerate natural gas dehydration unit's adsorption beds. The furnace uses a cascade temperature-pressure controller as shown in Figure 1. The master controller is the regeneration gas outlet temperature from the furnace, cascaded to the fuel gas pressure controller as the slave controller.

2.2 PID-Cascade Controller

PID controller is widely used in the industry due to its robust design and ease of use. The performance specifications of the system such as rise time, overshoot and settling time can be improved by tuning the PID parameters K_p, K_i and K_d of the PID controller, with each parameter providing a different effect to the controller reaction.

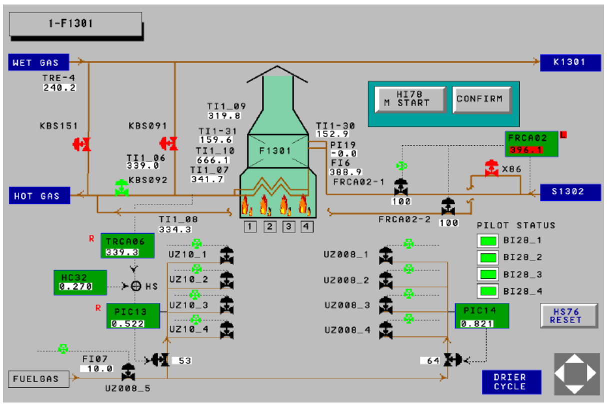

Figure 1. Cascade Temperature-Pressure Control for Regeneration Gas Furnace

The PID controller is mathematically represented as:

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

$$y(t) = \left[K_p e(t) + K_i \int_0^t e(t)d(t) + K_d \frac{d(e)}{d(t)} \right]$$

Where: $K_i = K_p/T_i$ and $K_d = K_p.T_d$

Figure 2 below shows the block diagram implementation for the furnace temperature-pressure cascade control system. From Figure 2, *P1* is the outlet temperature of the heated gas, which changes to the process temperature from disturbances from *d1*. The disturbances are acted on by controller *C1* which is the master temperature controller of the cascade control scheme. The *C1* master controller then sends the output as a remote set point to C2 slave pressure controller that will manipulate the *P2* process which has disturbances from *d2*.

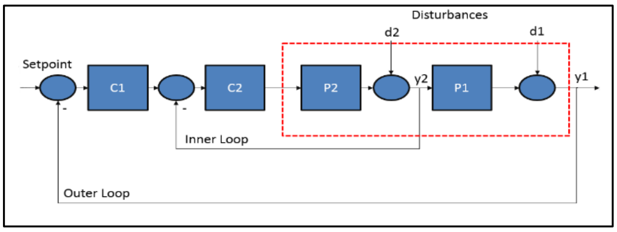

Figure 2. Cascade Control Block Diagram

The following are the transfer functions for the primary process parameter $P1$, which is temperature and secondary process parameter $P2$, which is pressure based on [1].

$$G_1(s) = \frac{1/90}{\left(s + \frac{1}{30}\right)\left(s + \frac{1}{3}\right)}$$

$$G_2(s) = \frac{1/10}{\left(s + \frac{1}{10}\right)(s + 1)^2}$$

A further simulation was conducted using another set of transfer functions, representing a change in process condition which is given as follows:

$$G_1(s) = \frac{1/80}{\left(s + \frac{1}{50}\right)\left(s + \frac{1}{5}\right)}$$

$$G_2(s) = \frac{1/15}{\left(s + \frac{1}{20}\right)(s + 1)^2}$$

2.2.1 Fuzzy-tuned Cascade PID Control System

A general fuzzy logic controller is shown in Figure 3, where it consists of four main parts which are fuzzification, rule base, inference engine and defuzzification. In this paper, the proposed technique is simulated using Simulink with Matlab's Fuzzy Logic Designer, based on the logic controller block of Figure 3.

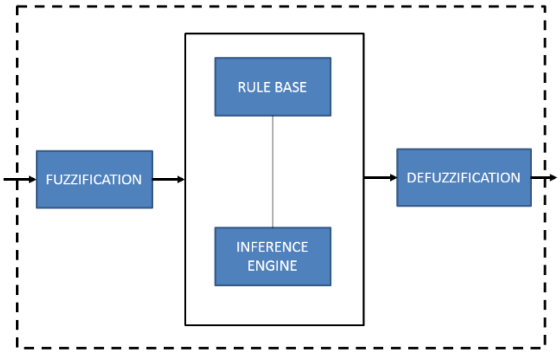

Figure 3. Fuzzy Logic Controller Block

2.2.2 Design of Fuzzy-Tuned Furnace Temperature-Pressure Control System

The self-tuning fuzzy PID works by continuously correcting the error between setpoint, $e(t)$ and the output, $de(t)$ which is the derivation of error as inputs into a fuzzy PID tuner. By continuously comparing these inputs, the PID parameters are tuned by fuzzy inference, which provides a nonlinear mapping from the error and derivation of error to PID parameters.

The fuzzy logic controller produces output that is multiplied with the *P*, *I* and *D* co-efficient of the PID-controller. By having this capability, the co-efficient of the conventional PID controller that is often not properly tuned for the nonlinear plant with unpredictable parameter variations can be addressed. To understand the proposed technique more, structure of the self-tuning fuzzy PID controller is shown in Figure 4.

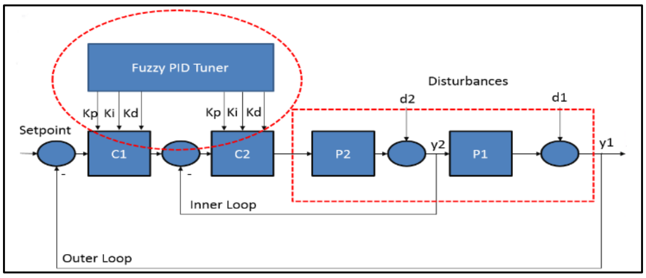

Figure 4. Structure of self-tuning fuzzy PID controller

The rules designed are based on the characteristics of the process transfer function and properties of the PID controller. Therefore, the fuzzy reasoning of fuzzy sets of outputs is gained by aggregation operation of fuzzy set inputs and the designed fuzzy rules. The aggregation and defuzzification method used are max-min and centroid method respectively.

Generally, the fuzzy rules are dependent on the plant to be controlled and the type of the controller and from practical experience. In regards to the above fuzzy sets of the inputs and outputs variables, Table 1 shows the fuzzy rules for Master Tuner and Table 2 shows the fuzzy rules for Slave Tuner. Example of how the rule is implemented is as follow:

Rule *i*: if *e(t)* is A_{1i} and *de*(*t*) A_{2i} then $K_{pi} = B_i$ and $K_{ii} = C_i$ and $K_{di} = D_i$.

Where $i = 1, 2, 3\ldots n$ and *n* is the number of rules. From the tables, there are five variables as input and five variables as output, hence, in the proposed design there are 25 fuzzy rules for the Master Tuner. For the Slave Tuner, the number of variables as input and output is seven which creates 49 fuzzy rules. The rules of the proposed fuzzy controller technique for the master and slave tuner is given in Table 1 and Table 2.

Table 1. Rules of the fuzzy inference for Master Tuner

De/e	NB	NS	ZE	PS	PB
NB	S	S	MS	MS	M
NS	S	MS	MS	M	MB
ZE	MS	MS	M	MB	MB
PS	MS	M	MB	MB	B
PB	M	MB	MB	B	B

Table 2. Rules of the fuzzy inference for Slave Tuner

De/e	NBB	NB	NS	ZE	PS	PB	PBB
NBB	AS	AS	S	S	MS	MS	M
NB	AS	S	S	MS	MS	M	MB
NS	S	S	MS	MS	M	MB	MB
ZE	S	MS	MS	M	MB	MB	B
PS	MS	MS	M	MB	MB	B	B
PB	MS	M	MB	MB	B	B	AB
PBB	M	MB	MB	B	B	AB	AB

On regards to the fuzzy structure, there two inputs to fuzzy inference, error *e*(*t*) and derivative of error *de*(*t*), and three outputs for each PID controller parameters i.e. K_{pi}, K_{ii}, K_{di}. In this paper, the Mamdani model is applied as a structure of fuzzy inference with continuous reference to the change in error and derivative of error to obtain the best value for K_p, K_i and K_d. Fuzzy inference block of the controller design is shown in Figure 5.

The membership functions of these inputs fuzzy sets are shown in Figure 6. The linguistic variable levels are assigned as NB: Negative Big, NS: Negative Small, ZE: Zero, PS: Positive Small PB: Positive Big. For the Slave Tuner, the additional variables are NBB: Negative Big-Big and PBB: Positive Big-Big. These levels are chosen from the characteristics of the PID controller. The ranges of these inputs are from -100 to 100, which are obtained from the absolute value of the system error and its derivative through the gains.

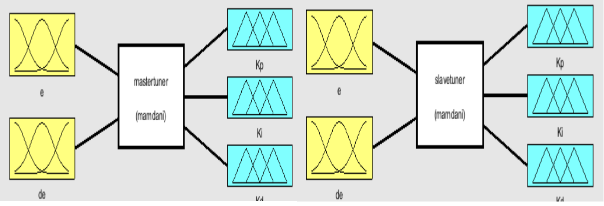

Figure 5. Fuzzy inference block

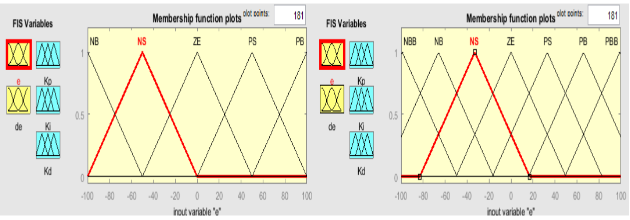

Figure 6. Membership functions of e(t) details for Master Tuner and Slave Tuner

Whereas the membership functions of outputs K_{pi} for master tuner and slave tuner are shown in Figure 7. The linguistic levels of these outputs are assigned as S: Small, MS: Medium Small, M: Medium, MB: Medium Big, B: Big. For the Slave Tuner, the additional linguistic levels are AS: Additional Small and AB: Additional Big.

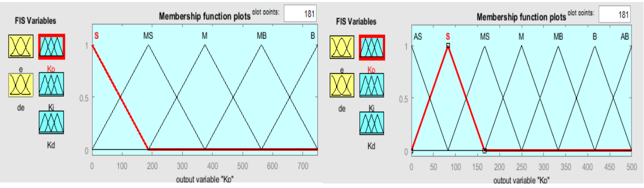

Figure 7. Membership functions of K_{pi}, K_{ii} and K_{di}.

3. MAIN RESULTS

Auto-tuner cascade PID controller based on fuzzy logic Simulink system block is shown in Figure 8. The value of the PID parameters K_p, K_i and K_d are tuned using signals from the fuzzy logic block. The fuzzy logic inputs are based on the error and changes in error between reference signals and output signals. The output of the simulation for comparison are shown in Figure 9 and Figure 10. The detailed analysis of the performance is depicted in Table 3.

The desired dynamic performance characteristics to be achieved for a good controller performance is having a quick rise-time, minimum delay time, quick settling, minimum overshoot and stability. The FL Auto Tuner provides continuous tuning feature which the controller performance maintains under changing process condition as in Table 3.

The change of response of a closed loop control system with respect to time is called dynamic response. The controller response can be analysed based on the following parameters.

1) Rise time (T_r): The rise time is given as the time required for the response of the system to reach its new setpoint value, typically within 10% or 90% of the steady state value respectively.
2) Settling Time (T_s): The settling time is given as the time taken for the response to reach and remains at the steady state value, typically with 2% to 5% error band.
3) Peak Overshoot/ Undershoot (M_p): The peak overshoot and undershoot refers to the ratio of the respective first peak values against steady state values.

4. CONCLUSION

In this paper, the performance of the proposed auto-tuner cascade PID controller utilizing fuzzy logic is compared with the conventional cascade PID controllers. The transfer function used to show the effectiveness of the proposed control technique is a furnace temperature system. The results show the advantage of the fuzzy inference systems as compared to conventional PID when different process transfer functions are utilized. From the results of the simulations, the auto-tuner cascade PID-Fuzzy controller has the potential for further development to cover greater change in process condition and non-linearity. Application in the process industry via Distributed Control System (DCS) can be further explored.

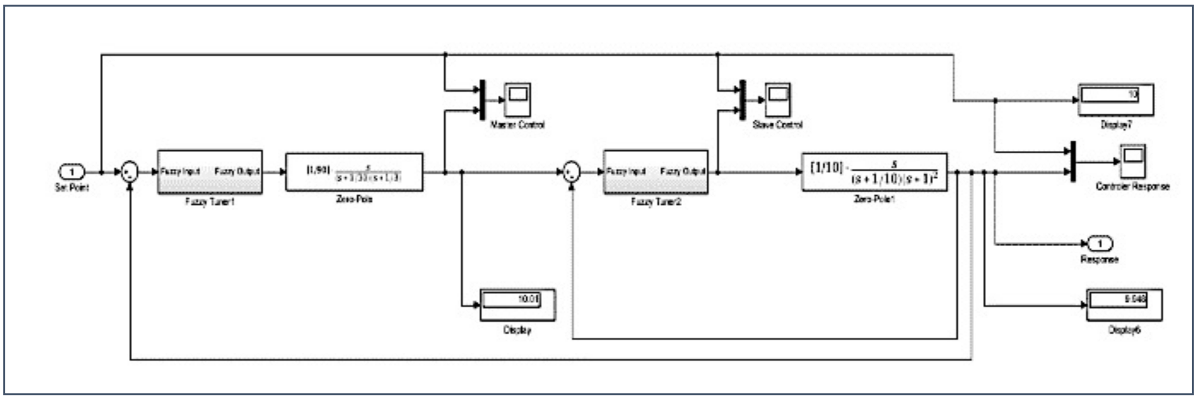

Figure 8. Simulink Block Diagram for Fuzzy Logic Auto-Tuner Cascade Controller

Table 3. Comparison Table of Time Domain Specification and Performance Criteria

Transfer Function	Controller Type	Rise Time	Settling Time	% Overshoot	% Undershoot
1	FL Auto Tuner	1.031s	16.372s	11.798%	1.114%
	Conventional	1.125s	19.641s	18.452%	0.912%
2	FL Auto Tuner	1.353s	21.035s	11.798%	1.343%
	Conventional	1.385s	31.306s	17.059%	0.982%

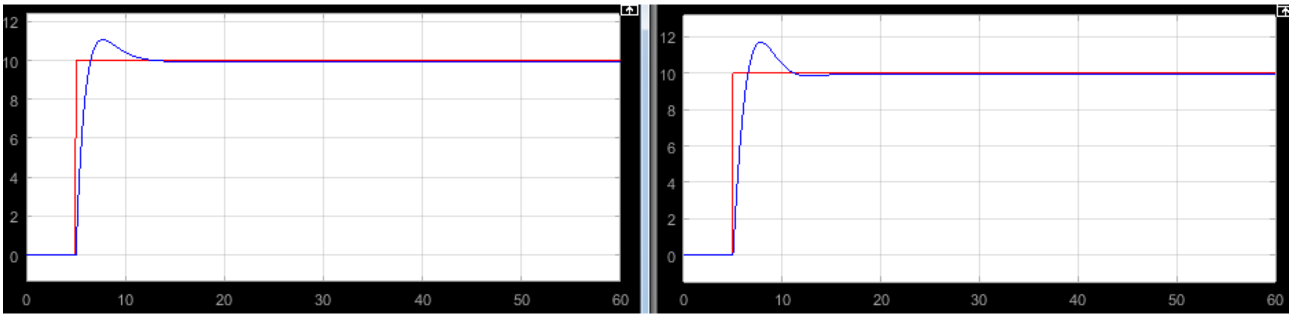

Figure 9. Step Change Response Comparison for Conventional and Auto Tuner Cascade Controller Process Transfer Function 1

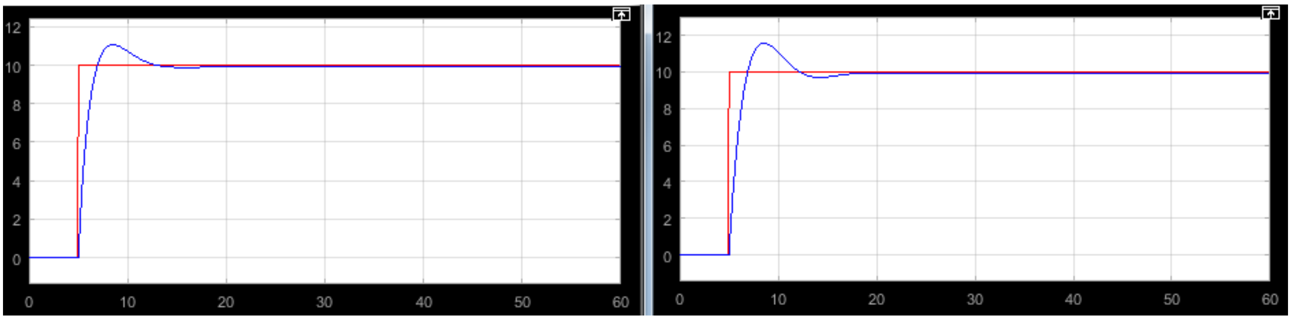

Figure 10. Step Change Response Comparison for Conventional and Auto Tuner Cascade Controller Process Transfer Function 2

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