Design an Optimal Fuzzy PID Controller for Herbal Machine Harvester with Gripping-Belt Speed

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Abstract. Today fuzzy logic is used to solve various engineering issues. In this paper a novel approach for tuning the PID controller for Gripping-Belt of Herbal machine Harvester speed control is proposed. Designing the values of proportional, integral and derivative constants are divided into three stages one for each constant. The Optimal Fuzzy system identifies the constants at each stage. The *Kp*, *Ki* and *Kd* are set by the optimized fuzzy logic controller to improve the performance of rise time, peak overshoot, oscillation and the settling time. Gripping-belt for herbal machine harvester with the control issues were discussed, given the gripping-belt approximation model with a control system using Matlab/Simulink and Fuzzy Logic Toolbox software kit built with herbal medicine harvester holding a simulation model and controller. The control system of the conventional fuzzy control, PID control and optimal fuzzy self-tuning PID control simulation results show that the optimal fuzzy self-tuning PID control for better dynamic response to achieve the desired control effect.

Keywords: Herbal machine harvester, Optimal fuzzy PID controller, Simulation, Speed control, SQP algorithm.

1 Introduction

With the continuous improvement of quality requirements harvest and rapid development of control theory, the new control technology applied to agricultural harvesting machine automation has become an inevitable trend. The gripping-belt should always track with the speed of the machine operating. However, Gripping-belt of herbal machine harvester with the existence of delay and inertia, due to harsh operating environment of agricultural machinery, and herbs grown by the low-lying density of the system parameters are also some uncertainty, so the system is uncertain nonlinear stochastic systems [1]. Traditional PID controller is linear, fuzzy control is not enough fast, the system is time-varying and nonlinear, so it is not easy to obtain satisfactory control quality.

Optimal fuzzy PID control can deal with uncertainties, time-varying, nonlinearity and sudden changes [2]. Studies have shown that fuzzy control because of its ambiguity, making it difficult to achieve high steady-state accuracy [3].In this paper, fuzzy

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control, conventional PID and optimal control combined to a form, optimal fuzzy PID control method. Fuzzy control has both the flexibility and adaptability advantages, but also PID control has stability and high accuracy. Trough optimization all these advantages will improve. Moreover, in a study of optimal design for fuzzy controllers, two relationships must be established: 1) design parameters and control nonlinearity, and 2) control nonlinearity and process performance.

This work is an attempt to undertake the development of a new analytical approach to the optimal design of fuzzy controllers. For an optimal system design using genetic algorithms, an overall performance index is proposed including several individual performance indexes. Finally, numerical studies are performed on several processes including nonlinearities due to time delay and saturation [6].

2 Methodology of Control System

Automatic control system without optimization of gripping-belt of herbal machine harvester is shown in Fig.1. The system consists of controller, stepper motor, hydraulic valves, hydraulic motors and speed sensors and other components [1]. System works by the controller and stepper motor direction of rotation of the corner; stepper motor and hydraulic valve rigid link directly to drive spool rotation, then driven by a hydraulic motor hydraulic valve work, the hydraulic motor speed sensors on the hydraulic motor speed feedback to the controller, so the controller can control the whole system.

The whole system formed a closed loop system. Fig. 2 shows the proposed methodology with respect to the data or parameter flow in off-line design [2].

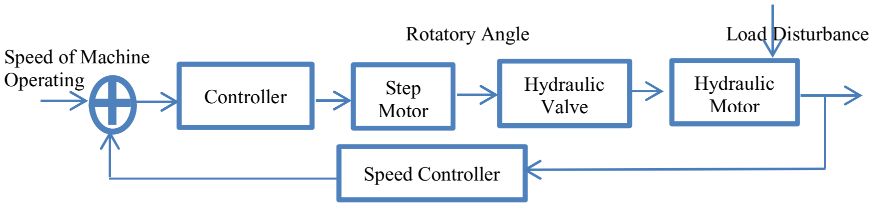

Fig. 1. Working principle of system

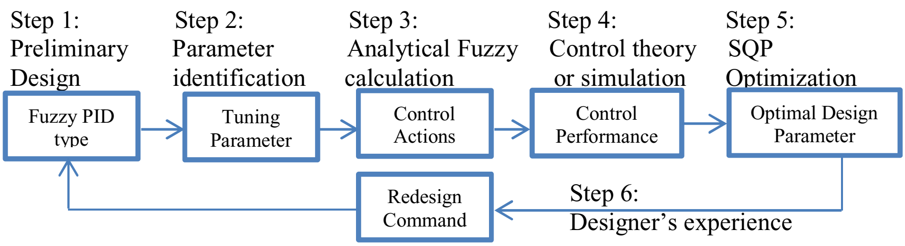

Fig. 2. Proposed methodology with respect to the data or parameter flows for optimal design of fuzzy PID controllers

In Step 1, the structure of a fuzzy PID controller is designed and the structural parameters are set for the preliminary design. The tuning parameters are identified in Step 2, while in Step 3 an analytical fuzzy calculation is performed, which produces a closed-form relationship between the design parameters and control action for the fuzzy inference. In Step 4, numerical simulation (or control theory) is used to obtain the control performance data. In Step 5, genetic-based optimizations are carried out to produce optimal design parameters. This also provides useful information for the redesign of the original system. Finally, if necessary, redesign is undertaken using the designer's expertise for further improvement to the control system. Note that the theoretical study in Step 3 makes the fuzzy controller transparent. This step is important since it will establish a close link between fuzzy control design technique and classical/modern control theory.

3 Design of Optimal Fuzzy PID Controller

Optimal control theory is one of the most important subsets of automatic control theory. The goal of optimal control is to find an ideal control input $u(t)$ in a specific time interval that can derive the plant along a trajectory so that the cost function is minimized [3].

$$\dot{X}(t) = f(X, u, t),$$

Where X represents the state of the system, u is the input, and t is the time. For a fixed final state control problem, the cost is:

$$J = \phi(x(T), T) + \int_{t_0}^{T} L(X, u, t)\, \mathrm{d}t \ ,$$

Where $\phi(x(T), T)$ is the final weighting function, which depends on the final state $x(T)$ and the final time T, and the weighting function $L(X, u, t)$ depends on the state and input at intermediate times in $[t_0, T]$. The goal of optimal control $u^*(t)$, on the time interval $[t_0, T]$ that derives the main system such that the cost function is minimized.

In this paper we use a fuzzy PID control method which employs a SQP optimization algorithm [5] to find the optimal solution by minimizing a well-defined cost function. As the result, the optimal fuzzy PID parameter tuner provides an online PID parameter tuning strategy for a standard PID controller as shown in Fig.3.

Our method in this article is based on optimal control theory and employs an optimization algorithm to find the optimal fuzzy PID parameter tuner that minimizes the cost function by combining fuzzy logic knowledge. The structure of the control system with a fuzzy PID parameter tuner is shown in Fig.3.

The objective of the system is to find the optimal control solution by evaluating the well-defined cost function and adjusting the parameters of three fuzzy PID parameters can be established. Three fuzzy parameter tuners are designed based on the mapping from error and derivative of error to PID controller parameters; $k_P(t)$, $k_i(t)$ and $k_d(t)$ as shown in Fig.4.

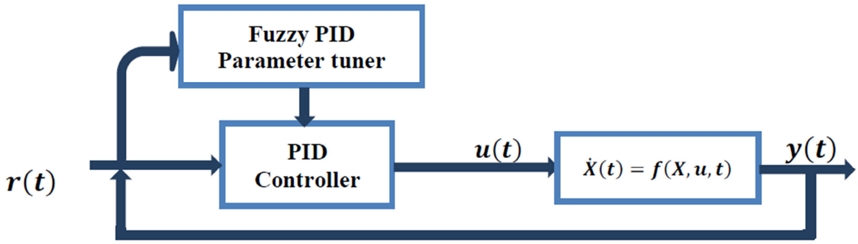

Fig. 3. General control system with a fuzzy PID parameter tuner and a PID controller

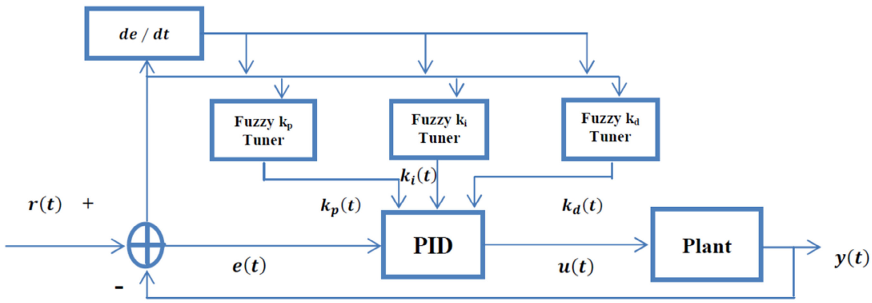

Fig. 4. Self-tuning fuzzy PID control structure

One major part of the proposed method is employ SQP (sequential quadratic programming) optimization algorithm to find the optimal fuzzy PID parameter tuners based on the cost function. The proposed method includes six steps:

1. Design the cost function,
2. Initial fizzy parameter tuner structure design,
3. Parameterization design from the initial tuner,
4. Establishment of constraints,
5. Optimization of the fuzzy PID parameter tuners,
6. Assessment of the rules.

A flow chart of the proposed method is shown in Fig.5.

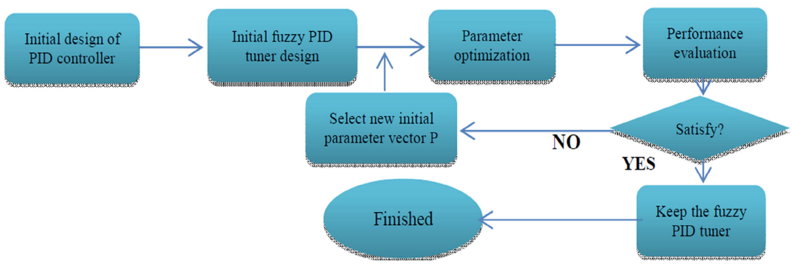

Fig. 5. Illustration of the proposed fuzzy tuner optimization method

Sequential quadratic programming (SQP) [6] which represent the state of the art in nonlinear programming methods can handle both equality and inequality constraints. This method is similar to Newton's method for constraint optimization. SQP algorithm is applied to search the space of the parameter vector until the minimal cost is reached. Although the Mathlab Optimization Toolbox provides 4 SQP algorithms, in this paper we use fmincon (Find minimum of constrained nonlinear multivariable function) because it is one kind of nonlinear programming optimization algorithms suitable for complex system optimization.

As shown in Fig.5 an optimization procedure will iterate many times to reach the final solution satisfying the design criteria. At each iteration, it is necessary to adjust the parameter vector such the sufficient improvement can be achieved. In the application of this paper, at each optimization iteration, in ninety-five percent of the cost could be achieved compared with the previous iteration cost, we consider improvement sufficient. It may be reasonable to change ninety-five percent to other to other values for a different application.

4 Principle of Fuzzy PID Controller

In this section we propose the fuzzy PID controller and show the results. In the next section we optimize the controller parameters and compare between the results of these two methods.

Fuzzy PID controller controls the PID parameters, online by using the fuzzy controller. In the first step it finds PID regulator 3 parameters (k_P, k_I and k_D) with tuning the error (e) and the rate change of error (ec) between the fuzzy relations. The controller adjust the k_P, k_I and k_D online according the control law, and then substitute the adjusted parameters into the PID equation to compare the results which be the output for the controller.

R_{ij} : if x is A_i and y is B_j Then: $u^{ij}(t) = K_P^{ij}\mathrm{e}(t) + K_I^{ij}\int e(t)dt + K_D^{ij}\dot{e}_{(t)}$;

$$K_I = K_P \frac{T}{T_I} \; ; \qquad K_B = K_P \frac{T_D}{T}$$

Where x denotes $e(t)$ and $x \in X$, y denotes $\dot{e}(t)$ and $y \in Y$, i=1,2,…,n and g=1,2,…,m.

T_I and T_D are regulator proportional, integral and differential time, and T is sampling period.

$u(t)$ denotes output variable.

Employing singleton fuzzifier, sum-product interface and center-average defuzzifier, the output of the fuzzy PID controller is expressed as:

$$u(t) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} A_i(x)B_j(y)u^{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} A_i(x)B_j(y)}$$

In this paper a fuzzy PID controller for the sample input speed deviation "e" $(v_0 - v)$ and the change rate of velocity deviation "ec" $[\frac{d}{dt}(v_0 - v)]$, motor control pulse output. PID controller, ΔK_P, ΔK_I and ΔK_D, the change of the K_P, K_I and K_D are used as the output of fuzzy controller.

The speed deviation change and speed deviation change rate of the domain location (-3,3), the output universe of ΔK_P, ΔK_I and ΔK_D is set at (-0.5,0.5), (-0.1,0.1), (-0.05,0.05). The fuzzy sets are divided into seven levels: {negative large, negative middle, negative small, zero, positive small, positive middle, positive large}, usually denoted as {NB, NM, NS, ZO, PS, PM, PB} [1].

The system uses triangular membership functions, and in the range of the two endpoints of the domain, in order to achieve a smooth curve membership function, respectively S-type and Z-type membership function. Membership functions curve corresponding to each variable shown in Fig.6 for inputs and Fig.7 for outputs.

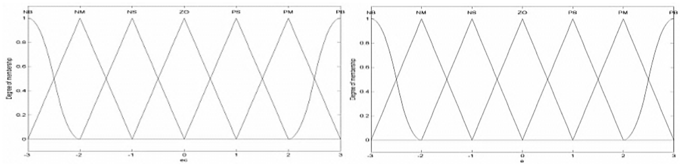

Fig. 6. The membership function curve of inputs; e & ec

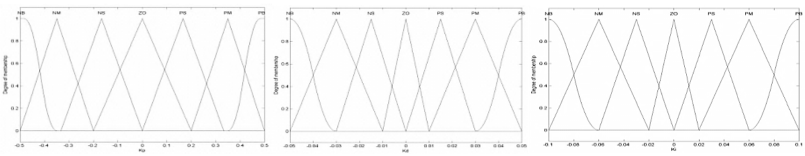

Fig. 7. The membership function curve of output; K_P, K_i, K_d

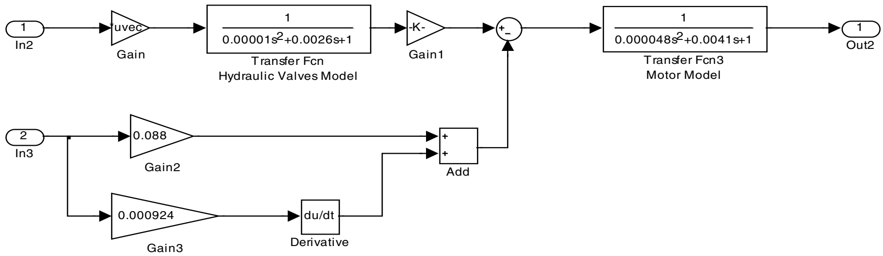

Fig. 8. Speed control subsystem block diagram

Based on the principle of fuzzy self-tuning PID, the use of "IF A and B THEN C and D and E" form of trial by repeatedly comparing the final set, and control rules, as shown in Table.1.

Table 1. Fuzzy rule table

EC/E	NB	NM	NS	ZO	PS	PM	PB
NB	PB/NB/PS	PB/NB/NS	PB/NM/NB	PM/NM/NB	PS/NS/NB	ZO/ZO/NM	ZO/ZO/PS
NM	PB/NB/PS	PB/NM/NB	PB/NM/NB	PM/NS/NM	PS/NS/NM	ZO/ZO/NS	NS/PS/ZO
NS	PM/NB/ZO	PM/NM/NS	PB/NS/NM	PS/ZO/NM	PS/ZO/NS	ZO/PS/NS	NS/PS/ZO
ZO	PM/NM/ZO	PM/NM/NS	PS/NS/NS	ZO/ZO/NS	NS/PS/NS	NS/PM/NS	NM/PM/ZO
PS	PS/NM/ZO	PS/NS/PM	ZO/ZO/PS	NS/PS/ZO	NM/PS/ZO	NM/PM/PS	NB/PB/ZO
PM	PS/ZO/PS	ZO/ZO/PB	NS/ZO/PS	NM/PS/PS	NM/PM/PB	NB/PM/PB	NB/PB/PS
PB	ZO/ZO/PB	ZO/ZO/PM	NM/PS/PM	NM/PM/PS	NB/PM/PB	NB/PB/PS	NB/PB/PB

Application of the PID parameter of fuzzy reasoning, found under the modified parameters into the calculated as follows [1]:

$$K_P = K_P' + \Delta K_P$$

$$K_I = K_I' + \Delta K_I$$

$$K_D = K_D' + \Delta K_D$$

Here: K_P', K_I' and K_D' are used for the previous setting good parameters.

Approximately the transfer function of the controlled object is: [7, 8].

$$G(s) = \frac{k_f \dfrac{k_q}{D_m}}{\left(\dfrac{s^2}{\omega_v^2} + \dfrac{2\xi_v}{\omega_v} s + 1\right)\left(\dfrac{s^2}{\omega_h^2} + \dfrac{2\xi_h}{\omega_h} s + 1\right)}$$

External load torque hydraulic motor angular velocity transfer function can be expressed as: [7, 8].

$$\frac{\omega_m}{T_L(s)} = \frac{-\dfrac{k_{ce}}{D_m^2}\left(1 + \dfrac{V_t}{4\beta_e K_{ce}} s\right)}{\dfrac{s^2}{\omega_4^2} + \dfrac{2\xi_h}{\omega_n} s + 1}$$

Simulation of the fuzzy PID control system using Simulink/Matlab R2011a version of 7.12.0 is shown in Fig.9 and the speed control subsystem block diagram is shown in Fig.10.

Simulation parameters were shown in Table.2.

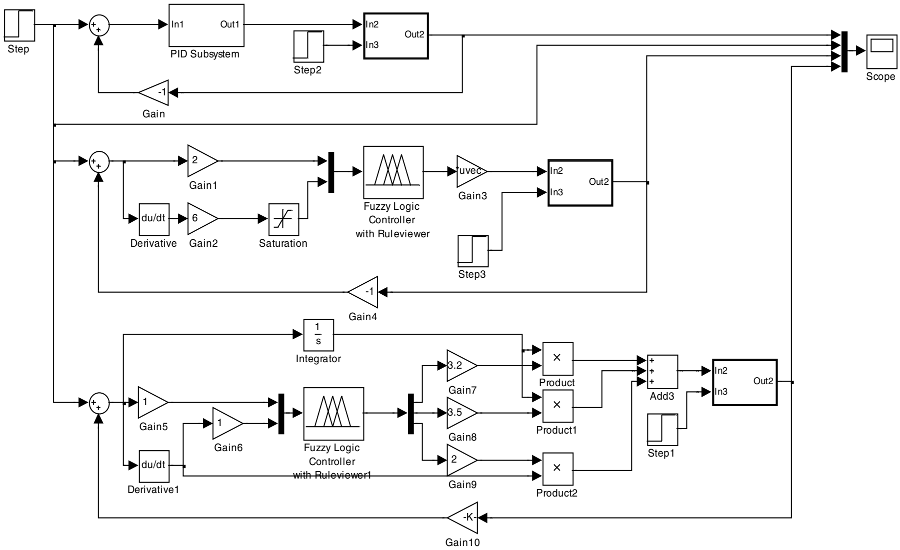

Fig. 9. Simulink simulation block diagram of PID control, fuzzy control and fuzzy PID control

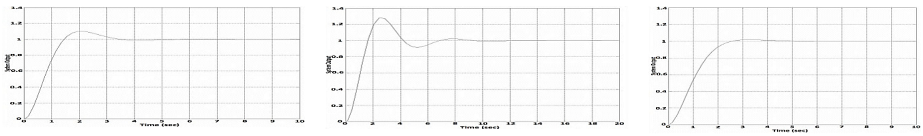

Fig. 10. PID, Fuzzy and Fuzzy PID control dynamic curve

Table 2. Simulation parameters

Symbol	Value	Symbol	Value
D_m (m^3/rad)	3.2×10^{-6}	V_t (m^3)	6.4×10^{-5}
β_e (pa)	1.7×10^{9}	ξ_v	0.41
k_{ce} (m^5/N.S)	9×10^{-13}	k_f	0.12
ω_v (rad/s)	314	ξ_h	0.3
ω_h (rad/s)	145	k_q	3.2×10^{-6}

5 Simulation and Results without Optimization

Simulation curve of PID, Fuzzy and Fuzzy PID controllers shown in Fig.10.

By comparing these three curves the following conclusion can be drawn, as shown in Table.3.

Table 3. Comparison of simulation results

Indicators Type	Peak Time s)	Adjustment Time (s)	Overshoot (%)	Steady state error (%)
PID	2.5	14	30	0
Fuzzy	2	7	10	4
Fuzzy-PID	3	5	0	0

6 Optimization Algorithm and Results

6.1 Algorithm

We chose to employ Sequential Quadratic Programming (SQP) [6], one of the gradient-based nonlinear programming optimization algorithms, to search the optimal parameter vector p for the given format of J. The reason for choosing SQP was for its effectiveness and capability of handling both equality and inequality constraints. It is provided by the Matlab Optimization toolbox.

$$J = \phi(t, t_0) + \int_{t_0}^{T} e^2(t)\,\mathrm{d}t$$

where $\phi(t, t_0)$ represents the level of overshoot and the integral term represents the overall performance. The optimization objective is to find the parameter vector p satisfying the design criteria. The determination of parameter vector p is important for the optimization process. The parameter vector should be chosen as the set of independent variables of the fuzzy tuner. It will include the membership function shape, position and scaling factors. The sample parameter vector p is represented as follows:

$$p = [p_1\ p_2\ \ldots p_k\ \ s_1\ \ s_2 \ldots\ s_m]$$

where $p_1\ p_2\ \ldots p_k$ are parameters determining the position and shape of the membership functions, $s_1\ s_2 \ldots\ s_m$ are scaling factors, k is the number of variables representing membership functions, and m is the number of scaling factors. The dimension of p for the optimization process needs to be decided carefully. It would be ideal to allow all parameters of the fuzzy tuners to be tuned. However, the computational complexity will become critical if p becomes too large.

Once the optimization procedure is completed, we will evaluate the results according to the cost function *J*, and decide if the optimization process should be repeated to discover whether any further performance improvements may be possible.

6.2 Result

The optimization algorithm will optimize the control performance by finding the optimal parameters of the controller. Fig.11 shows the progress of the cost function *J* during the optimization procedure.

Based on the predefined performance index, when the optimization process is finished, the parameter vector is:

$$p = [-1.35 \;\; 2.24 \;\; 0.73 \;\; 11.2 \;\; 0.62 \;\; 5.41 \;\; -2.13 \;\; 2.81 \;\; 2.32 \;\; -0.37 \;\; -1.39 \;\; 2.68 \;\; 0.49 \;\; 0.098 \;\; 4.52 \;\; 0.24 \;\; 1.58]$$

Optimization procedure makes optimized changes on the membership function curve of outputs.

Reducing the number of linguistic variables is another benefit of optimization of fuzzy controller. Here we had seven linguistic variables, and after optimization we have just five. The new membership functions are shown in Fig.12.

The dynamic curve (step response) also improves as shown in Fig.13.

In Table.4 comparison between the simulation results of fuzzy PID and optimal fuzzy PID controllers shows the benefits of our design method.

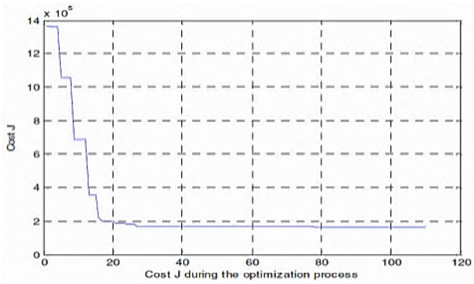

Fig. 11. Improvement of *J* during the optimization procedure

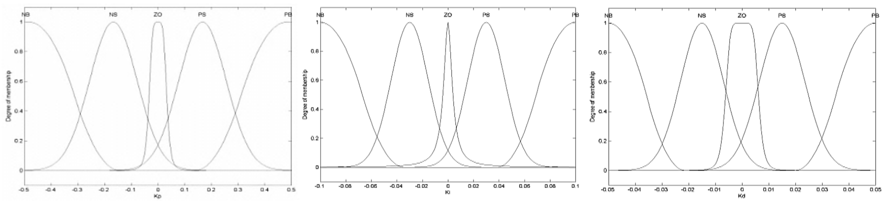

Fig. 12. The membership function curve of outputs after optimization; K_P, K_i and K_d

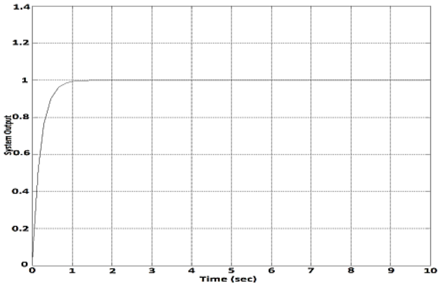

Fig. 13. The optimal fuzzy PID control dynamic curve

Table 4. Comparison of simulation results between fuzzy PID and optimal fuzzy PID controller

Indicators Type	Peak Time (s)	Adjustment Time (s)	Overshoot (%)	Steady state error (%)
Fuzzy PID	3	5	0	0
Optimal Fuzzy PID	1	2	0	0

7 Conclusion

In this paper, a new optimal fuzzy PID design method is proposed by utilizing the SQP nonlinear programming optimization algorithm. The simulation results of herbal machine harvester motor application are presented. It has turned out that with the optimization algorithms, the fuzzy PID optimal controller design and the desired overall control performance can be achieved by selecting a proper cost function. Also the parameter vector and optimization algorithm play key roles in this approach.

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