Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management
Dubai, UAE, March 3 – 5, 2015

Fuzzy strategy with anti-overshoot technique for electronic throttle control

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***Abstract*—Electronic throttle actuator is a nonlinear device which consists several effects of delay time, transmission friction, throttle plate friction and return spring load. Each of the effects is a particular problem for accurate control of electronic throttle controller, but the big problem one is a return spring load. It can lead the actuator to overshoot and undershoot behaviors. To eliminate the behaviors, this paper presents a fuzzy strategy base on original design and anti-overshoot technique. First, the fuzzy strategy is a discrete fuzzy PI controller which provides easy tuning, robustness and rapid development. Second, the anti-overshoot technique is an anti-windup algorithm with simple architecture. Both of the presented are designed following cascade feedback control scheme, and also embedded into microcontroller chip for real experiment. In addition, this paper also reveals a single phase driver circuit for hardware setup. According to the experiment results, with best parameters for controller, the fuzzy strategy with anti-overshoot technique can carried out effectively, and guarantee a performance by using standard criteria such as an integral of square error (ISE), an integral of absolute error (IAE), an overshoot max (OVM) and a settling time max (STM).**

Keywords-electronic throttle control; fuzzy control; fuzzy strategy; anti-windup; anti-overshoot;

I. INTRODUCTION

Nowadays, various vehicles are commercially used in both public transportation and private transportation. Such the vehicles are motor bikes, cars, trains, boats as well as aircrafts. They are driven by internal combustion engine that is either 2-stroke or 4-stroke systems. Most of the engines are controlled by intelligent electronic control unit (ECU) for modern trend, high performance, rapid tuning, easy maintenance, safety, low fuel economy and less environment pollution [1]. With high performance point, power of engine is depended on air to fuel ratio inside cylinder for combustion process. Obviously, air mass and fuel mass are importance. In regulation of air mass, an electronic throttle valve (ETV) is operated, and the ETV is also controlled by ECU. Therefore, the engine performance is depended on a response of the ETV [2].

In a last decade, to control the ETV practically, several electronic throttle control strategies have been proposed. Fashions of classical proportional-integral-derivative (PID) controller with and without compensators are presented that the compensators are: a feed-forward table, a nonlinear friction, a limp-home friction and a spring load. From classical control to modern control, an adaptive technique and self-tuning algorithms are employed to operate with PID controller simultaneously. In the area of robust control, a simple sliding mode and a second-order sliding mode controllers are used. Furthermore, the granular computing (GrC) as: fuzzy logic, neuron network and genetic algorithm are applied to support classic/modern controllers, and to perform itself.

Recently, 2013 and 2014, control strategies for ETV have been interesting for contribution. The tracking control of nonlinear hysteretic system is proposed that is based on intelligent fuzzy logic design. It also works with close-loop Back-propagation tuning for center values [3]. The discrete-time enhanced minimal control synthesis algorithm is presented which consists of direct adaptive scheme, discrete-time adaptive integral action and adaptive robust term [4]. The multi-adaptive controller by using PID control, feedforward compensation and nonlinearity compensation is described [5]. As the recent proposed publications, their method can regulate the ETV effectively without both untracked and overshoot behaviors from imposed by driver. Nevertheless, this paper presents the different methods of an ETV controller and anti-overshoot technique. A simple fuzzy PI structure well-designed in [6] is implemented for ETV controller. With a fuzzy PI controller in [6] have thoroughly proved and well-understood many years ago for simple structures, easy tuning, excellent tracking performance and high robustness. The simple anti-windup design in [7] is also implemented for anti-overshoot technique. Moreover, we describe and develop the single phase motor driver circuit for hardware setup in real practical. The

This research is supported by Thailand Research Fund under grant RGJ-PhD/172/2550.

experiment results employ standard criteria: ISE, IAE, OVM and STM for performance index.

The organization of this paper is as follows. Section 1 deals with the introduction and Section 2 details the ETV structure. The design of the fuzzy PI controller with anti-overshoot technique is addressed in Section 3. Experiment and results are presented in Section 4 while the conclusion is provided in Section 5.

II. ELECTRONIC THROTTLE VALVE

The electronic throttle valve is consisted of three dynamic parts: an electric motor, a gearbox and a return spring. There are extremely influencing to design precisely control algorithm. The ETV structure is shown in Fig. 1.

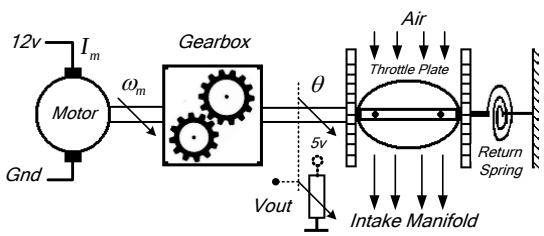

Figure 1. Electronic throttle valve structure.

In motor part, the mathematical model of electric part can be described by

$$Vi - VLm - VRm - Vb = 0 \quad (1)$$

$$Vi - Vb = Lm\frac{di}{dt} + iRm \quad (2)$$

$$i = \frac{Vi - Vb}{sLm + Rm} \quad (3)$$

, and mechanic part:

$$Tm - Tb - TJ - Tl = 0 \quad (4)$$

$$Tm - b\omega - J\frac{d\omega}{dt} - Tl = 0 \quad (5)$$

$$\omega = \frac{Tm - Tl}{Js + b} \quad (6).$$

During a motor is operated, in the gearbox part, both transmission friction and backlash nonlinear behaviors are occurred. They can be definite as delayed-time behavior. Torque from the motor through the gearbox controls a throttle plate to ether open or close; conversely, a force from a return spring drives throttle plate in opposite direction. The return spring is huge load that is based on nonlinear behavior. From the three parts, the ETV is performed base on hysteresis characteristic. For more understanding, both the backlash nonlinear and the nonlinear return spring can be shown characteristics in Fig. 2.

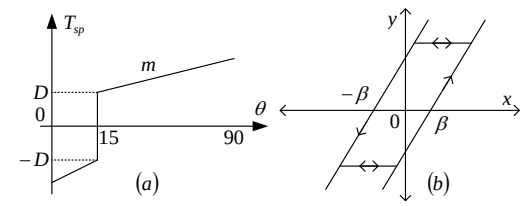

Figure 2. (a) A nonlinear return spring, (b) A backlash characteristic.

III. CONTROLLER DESIGN

Classical feedback analog control is a PID controller that is widely used in many industrial processes. To transform the analog PI to a discrete PI, a relationship between s-form and z-form [6] is employed as

$$s = \frac{2}{T}\frac{\left(1 - z^{-1}\right)}{\left(1 + z^{-1}\right)} \quad (7).$$

Using (7) to a conventional PI incremental control,

$$\Delta U_{PI}(KT) = K_p\{e(KT) - e(KT-1)\} + K_i\{e(KT) + e(KT-1)\} \quad (8)$$

where K_p and K_i are controller gains. From [6], fuzzy logic theory and the PI control are combined; hence, the discrete fuzzy-PI controller (FPIC) is established. Typically, a process of fuzzy control system consists of essentially 3 parts such as fuzzification, fuzzy inference and defuzzification. The FPIC is derived by using an error and a rate of error for fuzzification process, four rule bases and min-max Mamdani's method for fuzzy inference process and a center of area calculation for defuzzification process. In fuzzification process, input membership functions are shown in Fig. 3

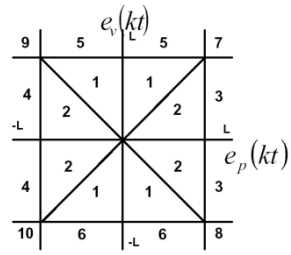

Figure 3. Regions of the fuzzy PI controller input.

As the defuzzification process, it is a fuzzy controller output management that a center of area technique is used for controller output calculation. Thus, the final formulas of each input region are defuzzified as following:

$$\Delta u_{pi}(kt) = \frac{L\{K_i e_p(kt) + K_p e_v(kt)\}}{2\{2L - K_p|e_v(kt)|\}} \quad \text{Area 1}$$

$$\Delta u_{pi}(kt) = \frac{L\{K_i e_p(kt) + K_p e_v(kt)\}}{2\{2L - K_i|e_p(kt)|\}} \quad \text{Area 2}$$

$$\Delta u_{pi}(kt) = 0.5\{K_p e_v(kt) + L\} \quad \text{Area 3}$$

$$\Delta u_{pi}(kt) = 0.5\{K_p e_v(kt) - L\} \quad \text{Area 4}$$

$$\Delta u_{pi}(kt) = 0.5\{K_i e_p(kt) + L\} \qquad \text{Area 5}$$

$$\Delta u_{pi}(kt) = 0.5\{K_i e_p(kt) - L\} \qquad \text{Area 6}$$

$$\Delta u_{pi}(kt) = -L \qquad \text{Area 7}$$

$$\Delta u_{pi}(kt) = 0 \qquad \text{Area 8, 9}$$

$$\Delta u_{pi}(kt) = L \qquad \text{Area 10}$$

The overall of discrete fuzzy-PI control systems are shown in Fig. 4; apparently, it is adjusted by four parameters: error gain K_i, rate of error gain K_p, output gain K_u and input membership length L.

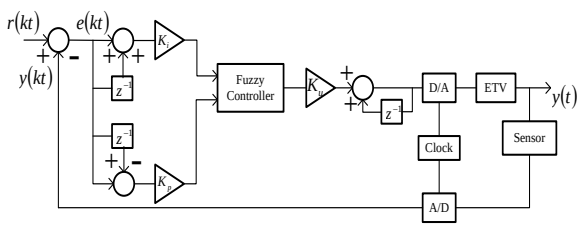

Figure 4. Bilinear discrete fuzzy-PI control system.

According to the ETV hysteresis characteristic with the huge load of spring as mentioned in Section II, there is dramatically difficult to control angle of throttle plate in case of unit step acceleration input because the overshoot behavior of response signal is appeared. Therefore, to eliminate the overshoot behavior, an anti-windup technique is applied to combine with the discrete fuzzy-PI controller. The system is illustrated in Fig. 5.

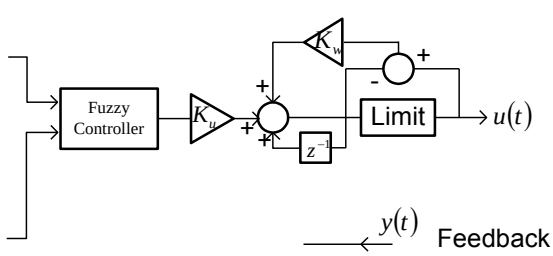

Figure 5. Discrete fuzzy-PI control with output anti-windup system.

IV. Implementation and Results

The electronic throttle control system is organized on single input single output (SISO) feedback control strategy as shown in Fig. 6. In design for experimental as Fig. 6, a dsPic30f2010 microcontroller is used for the controller part to generate PWM control signal for TLP250 isolator, and the both discrete fuzzy-PI and anti-windup formulas are embedded into the microcontroller. The TLP250 isolator is applied to amplify the control signal from 5 volts to 12 volts. An IRF840 MOSFET is employed for motor driving; also, the MOSFET can source high current up to 8 amperes. The single phase motor driving circuit is described in Fig. 8. The series of electronic throttle valve is a HITACHI SERA576-01 model that is entered in NISSAN SUNNY. Two electrical supplies are: a main supply is 12 volts for all parts; a controller supply is 5 volts. All equipments of the electronic throttle control system are shown in Fig. 7.

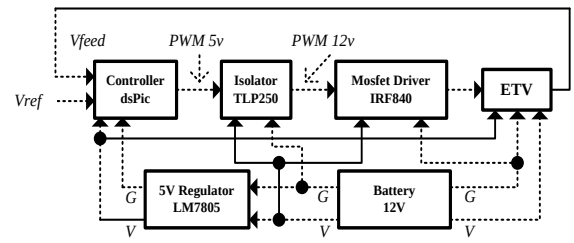

Figure 6. Electronic throttle control organization.

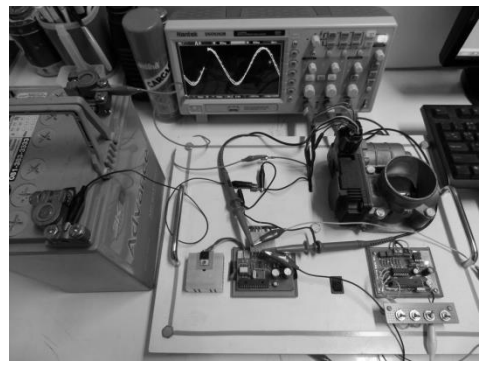

Figure 7. Experimental setting.

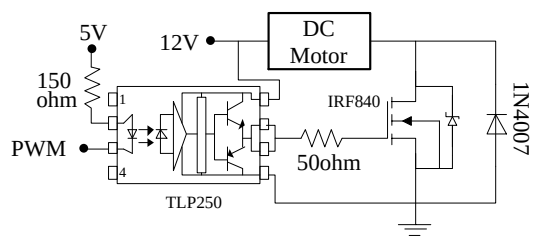

Figure 8. Single phase motor driver.

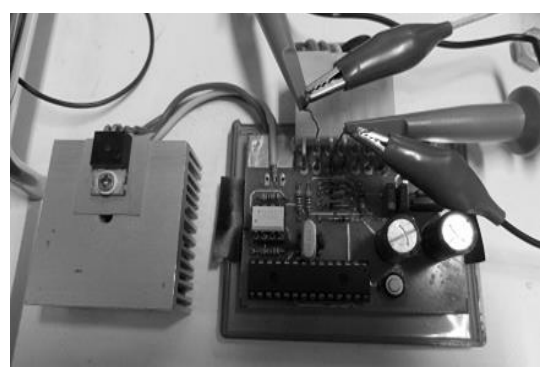

Figure 9. The microcontroller and the motor driver.

For all parameters in experimentation, a sample time of controller is 1 millisecond; the controller gains are: K_p =20.0, K_i =0.043, K_u =3, L =250 and K_w =1.05; the PWM control signal is 200 Hz. Three throttle input situations are: single-ramp acceleration, sine acceleration and multi-step acceleration as shown in Fig. 10.

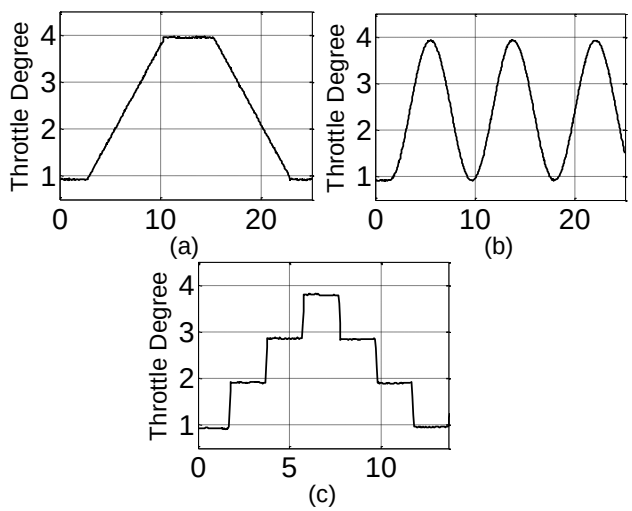

Figure 10. (a) single-ramp acceleration, (b) sine acceleration and (c) multi-step acceleration.

First testing, the discrete fuzzy-PI controller without anti-windup is used, and the parameters are set as: K_p =20.0, K_i =0.043, K_u =3, L =250 and K_w =0.0. From the results, Fig. 11 and Fig. 12 show tracked responses of single-ramp acceleration and sine acceleration respectively during 25 seconds. In Fig. 11, a reference voltage is slowly increased from 1 volt to 4 volts in 7 seconds, and is slightly decreased down to 1 volt. There's average of tracked error is 0.035 volt. In Fig. 12, a reference voltage is smoothly sine wave on 0.1 Hz. There's average of tracked error is 0.057 volt. Fig. 13 shows transient response of multi-step acceleration. Each step is added by a volt every 2 seconds that the rise time of step is 50 milliseconds. In the same for step down, the reference voltage is decreased by a volt every 2 seconds. There's overshoot behaviors are appeared because of spring force; consequently, the average of error is 0.038 volt.

Second testing, the discrete fuzzy-PI controller with anti-windup is used, and the parameters are set as: K_p =20.0, K_i =0.043, K_u =3, L =250 and K_w =1.05. Obviously, most of parameters are same values except the K_w ; therefore, the tracked responses of single-ramp acceleration and sine acceleration are similar. But, for multi-step acceleration, the transient response is different. The overshoot behaviors are eliminated as shown in Fig. 14, and the average of error is 0.047 volt. For performance indexes (J) are shown in Table 1.

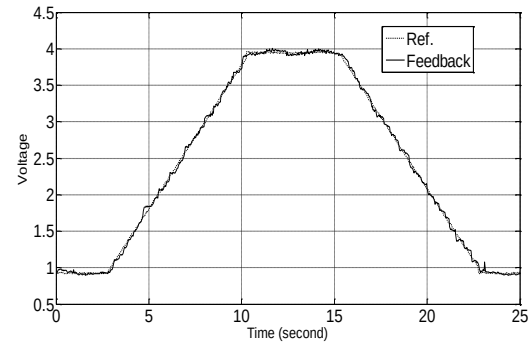

Figure 11. Single-ramp acceleration input.

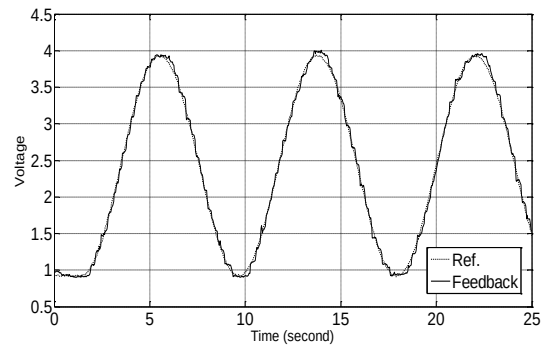

Figure 12. Sine acceleration input.

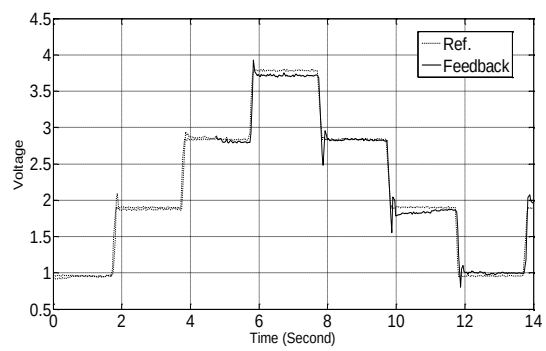

Figure 13. Transient response of multi-step acceleration input is controlled by FPIC without anti-overshoot technique.

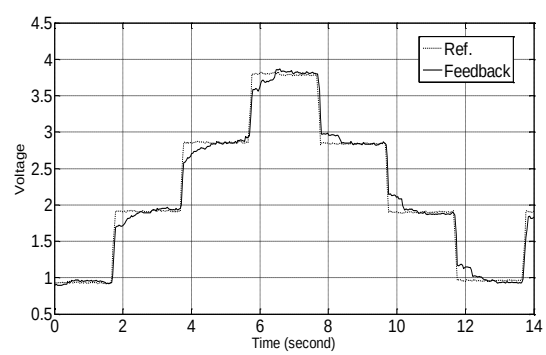

Figure 14. Transient response of multi-step acceleration input is controlled by FPIC with anti-overshoot technique.

TABLE I. THE CRITERIONS OF ELECTRONIC THROTTLE CONTROL

Situation	IAE (Volt)	ISE (Volt)	OVM (Volt)	STM (Second)
Single-Ramp acceleration	0.035	0.0027	0	0
Sine acceleration	0.057	0.0038	0	0
Multi-Step acceleration (FPIC without anti-overshoot technique)	0.038	0.0055	0.0196	0.38
Multi-Step acceleration (FPIC with anti-overshoot technique)	0.047	0.0076	0	0.72

V. CONCLUSION

In this paper, the anti-overshoot technique using anti-windup structure is presented to combine with the discrete fuzzy PI controller in [6]. As the combined system, it is used to control the electronic throttle valve in all situations of input: single-ramp acceleration, sine acceleration and multi-step acceleration, to eliminate the overshoot behavior. In real experiment, the discrete fuzzy PI controller with anti-overshoot technique is embedded into a microcontroller, and the single phase motor driver circuit is described. According to experimental results, Fig. 11 and Fig. 12 show that the combined controller can track to the single-ramp and sine accelerative inputs effectively, and Fig. 14 also show that the overshoot problem is eliminated explicitly.

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BIOGRAPHY

Anurak Jansri was born in Chiang Mai, Thailand. He received the B.IT., M.Eng., and D.Eng. degrees from King Mongkut's Institute of Technology Ladkrabang (KMITL), Bangkok, Thailand, in 2002, 2007, and 2013, respectively. He is currently a researcher and lecturer at the Faculty of Technology and Innovation, Bangkok Thonburi University. His main research interests are controls and computer softwares for robotic, vehicle and industrial applications.

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Suwilai Phumpho (formerly Areejit) was born in 1980 in Thailand's Samutprakarn province. In 2003, he graduated summa cum laude with a bachelor's degree in Electronic Engineering from Mahanakorn University of Technology (MUT). In 2008, Mr. Phumpho earned a master's degree in Information Engineering from King Mongkut's Institute of Technology Ladkrabang (KMITLX) and, in 2014, completed his doctoral degree in Electrical Engineering from the Faculty of Engineering, KMITL. His research interests center around chaotic applications, mechatronic systems, control applications, industrial process control, and renewable energy.