Speed Control System of Brushless DC Motor Using Fuzzy Logic PID Controller in Automatic Guided Vehicle

Pyong-Suk Ri, Jin-Myong Hwang, Jin-Song Kim, Yong-Kyong Kim, Kum-Song Ri*

Faculty of Mechanical Science and Technology, Kim Cheak University of Technology, Kyogudong No.60, Yonggwang street, Pyongyang 950003, Democratic People's Republic of Korea

***Corresponding Author**

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ABSTRACT

Brushless DC motors are employed in wide variety of applications including aerospace, robotics, healthcare and so on due to their advantages such as high operating life, high efficiency, high dynamic response. This paper describes speed control system of BLDC motor in Automatic Guided Vehicle using Fuzzy PID controller. The signal obtained from Hall-effect sensor of the motor can be analyzed to measure velocity of the robot. Fuzzy PID controller with high speed response characteristic and robustness is designed to maintain velocity of the robot. Thus workpieces on the robot don't fall down under the several conditions such as setting off and stopping of the robot and sudden load variation. Using designed FPID controller, we can calculate output voltage and drive BLDC motor by using Pulse Width Modulation method. Several simulations using MATLAB are taken to assessment the advantages of the proposed method. This control system reveals high speed response characteristics and reliability in running operation especially under the varying load condition.

Keywords: BLDC motor, Hall-effect sensor, Automatic Guided Vehicle, Fuzzy PID, speed control, PID controller

INTRODUCTION

It is very important task to design speed control system of BLDC motor with high performance. When the robot sets off and stops, and the load varies, workpieces on it may fall down because of the sudden change of robot speed. Moreover, under sudden load variations the rotation torque will increase suddenly and the flowing current will be exceeded. If this state lasts longer than desired time or this case will be repeated, it leads to breakdown of the motor. In order to control robot speed, the rotating speed of it should be measured ahead. The control of BLDC motor can be classified as sensor-based control and sensor-less control. In sensor-based control, the stator winding is excited based on rotor position which is measured using Hall-effect sensors[1]. BLDC motors often incorporate either internal or external position sensors to measure the actual rotor position[2]. The rotating speed of the BLDC motor can be measured using Hall-effect sensors which are placed on the stator. Each time the permanent magnets pass the sensor, pulse signals are generated that are used in speed measurement. The more the number of the magnets, the more the number of the generated pulse signals and improve the accuracy of the speed measurement.

PID control is widely used not only in process control but also in BLDC motor control system. The performance of a speed controller mainly depends on tuning of PID gains. Tuning is nothing but finding appropriate proportional, integral, and derivative gains of PID controller to meet the desired performance[1]. Conventional PID controller is widely used in linear control system because of its simple structure and high robustness. However, most of processes and control system have nonlinearity and it is impossible to make exact mathematical model of the object. Thus, high controllability cannot be obtained through only conventional PID control scheme.

Fuzzy control is knowledge-based or rule-based control technique. The purpose of it is to describe the experiences of the operator as fuzzy control rules and then realize operator-similar control based on inference.

Fuzzy control can be used when the mathematical model of the object is ambiguous or unknown[6]. Fuzzy control can be applied to complicated object efficiently; while it has some drawbacks. For example, the static error still remains because it doesn't have integral operation. Fuzzy PID controller is used to improve static characteristics of the fuzzy controller[3].

Conventional PID controller can exert satisfactory performance when the controlled object is stable or the output is in normal state. But, in the case of sudden change of the object or being in the abnormal state, PID controller cannot fulfill control task alone. Thus, Fuzzy PID controller which can tune PID coefficients based on fuzzy logic are adopted to realize such kind of control task. For FPID is combination of fuzzy control and PID control, so it can incorporate the advantages of them, which are good dynamic characteristic in fuzzy control and good static characteristic in PID control, to obtain better control performance.

In this paper, we described speed control system of the BLDC motor in Automatic Guided Vehicle using Fuzzy PID controller. The real speed of the robot is measured by using Hall-effect sensor. The error between the real speed and reference value and the change of the error can be used to input signal of fuzzy logic controller in order to obtain PID coefficients. MATLAB simulation results demonstrate that the system reveals faster speed response and higher robustness when using proposed method than conventional PID.

The remainder of this paper is organized as follows: Section 2 shows related works. Section 3 describes modelling of BLDC motor. Section 4 shows speed control system of BLDC motor using Fuzzy PID. Section 5 describes hardware implementation of the robot control system. Section 6 shows simulation results using MATLAB. Section 7 concludes the paper.

Related Works

Chung-Wen Hung, Jhih-Han Chen, Ke-Cheng Huang[7] proposes a Hall sensor-based circuit for correcting the errors occurring in the speed measurement of a brushless DC (BLDC) motor. Although the poles of the rotor are always placed with a uniform angular separation, the Hall sensors may not. The angular misalignment between the poles and the Hall sensors will cause errors in the speed measurement of the motor. They designed and implemented a new correction circuit which can reduce measurement error below 45% using FPGA. E.A. Ramadan, M. El-bardini, M.A. Fkirin[8] realized adaptive fuzzy speed control system of DC motor using FPGA. They used adaptive fuzzy logic control algorithm in order to overcome nonlinearity of DC motor. Hardware was implemented by using FPGA and verified tracking and other performances under operating condition. Akash Varshney, Deeksha Gupta, Bharti Dwivedi[2] proposed fuzzy PID controller which can exert stable speed response under varying load. Modelling and controller design were carried out using MATLAB and the performance comparison between conventional PID and fuzzy PID were conducted. Kandiban, R. Arulmozhiyal[9] proposed speed control system of BLDC motor using adaptive fuzzy PID controller and simulated using MATLAB. This paper proves that proposed adaptive fuzzy PID controller has stable speed response when the load varies. K. Sarojini Devi, R. Dhanasekaran, S.Muthulakshmi[10] introduced a new method to improve speed control performance of BLDC motor using fuzzy PID controller. Here, self-tuning fuzzy PID control technique is used to minimize overshoot and shorten setting time. Songmao Zhang, Yunliang Wang[11] simulated speed control system of BLDC motor based on optimized fuzzy PID control algorithm. They proved that fuzzy PID control algorithm has faster response, higher control precision and robustness than conventional PID or fuzzy control. Devendra Somwanshia[12] used fuzzy PID and conventional PID controller to compare control speed control performances of DC motor. They used fuzzy controller to tune PID coefficients and simulate the system using LabVIEW.

In most of related works, there were only simulation tests about motor speed control system using MATLAB or LabVIEW, or some kind of simple experiment device for investigation purpose. Moreover, there doesn't exist any research paper which describes speed control system with high speed response and robustness under different situations such as setting off and stopping of vehicle and sudden load condition when BLDC motor is used to drive Automatic Guided Vehicle.

This paper describes FPID control system of BLDC motor that is used to drive Automatic Guided Vehicle under different situations, hardware and software implementation and simulation results using MATLAB.

Modelling of BLDC motor

In order to configure speed control system of BLDC motor, dynamic model should be made beforehand. General mathematical model of BLDC motor is as follows.

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a & L_{ab} & L_{ac} \\ L_{ba} & L_b & L_{bc} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

Here, u_a, u_b, u_c are three phase voltages(V), e_a, e_b, e_c are three phase back-electromotive forces(V), R_a, R_b, R_c are three phase inductive resistances(Ω), i_a, i_b, i_c are three phase currents(A), L_a, L_b, L_c are three phase self-inductances(H), $L_{ab}, L_{ac}, L_{ba}, L_{bc} L_{ca}, L_{cb}$ are three phase mutual-inductances(H). For convenience in analysis, resistances, self-inductances and mutual-inductances are same respectively.

$$L_a = L_b = L_c = L, L_{ab} = L_{ac} = L_{bc} = L_{ca} = L_{cb} = M\,,\ R_a = R_b = R_c = R$$

Eq. (1) can be written as follows.

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{2}$$

For the three-phase symmetrical motor, $i_a + i_b + i_c = 0$,

$$Mi_a + Mi_b + Mi_c = 0\,,\ Mi_b + Mi_c = -Mi_a\,,\ Mi_a + Mi_c = -Mi_b\,, Mi_a + Mi_b = -Mi_c$$

Eq. (2) is presented as following equation.

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} P \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{3}$$

where P is derivate operator with time. $P = \frac{d}{dt}$

$$u_a = Ri_a + (L-M)\frac{d}{dt} i_a + e_a$$

$$u_b = Ri_b + (L-M)\frac{d}{dt} i_b + e_b$$

$$u_c = Ri_c + (L-M)\frac{d}{dt} i_c + e_c$$

Torque value can be expressed by back-electromotive force and current of each phase.

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega = K_t I \tag{4}$$

where ω is angular velocity of BLDC motor(rad/s), T_e is electromagnetic moment of motor, K_t is moment coefficient.

$$I = i_a + i_b + i_c$$

When there is no load, electromagnetic moment of motor is expressed as:

$$T_e = B_M \omega + J_M \frac{d\omega}{dt} \tag{5}$$

When there is load, T_e is,

$$T_e = T_L + B_M \omega + J_M \frac{d\omega}{dt} \tag{6}$$

where T_L is load torque($N \cdot m$), B_M is friction coefficient of BLDCM($N \cdot m \cdot s / rad$), J_M is motor inertia ($kg \cdot m^2$).

$$T_L = J_L \frac{d\omega}{dt} + B_L \omega \tag{7}$$

where J_L is load inertia($kg \cdot m^2$), B_L is damping coefficient($N \cdot m \cdot s / rad$).

The equation of state of motor is written as:

$$P\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \frac{1}{L-M} & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & \frac{1}{L-M} \end{bmatrix} \left\{ \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \right\} \tag{8}$$

Parameters of motor are resistances, inductances of each phase and inertia and friction of motor and load. To design PID controller, parameters of BLDCM and load should be determined. Varying parameters are R, J_M, J_L, B_M, B_L. These influence on speed response of BLDCM.

Speed control system of BLDCM using Fuzzy PID controller

Fuzzy logic control theory

Fuzzy controller is composed of fuzzification, rule inference and defuzzification. The error of velocity and change of error are expressed:

$$e(k) = \omega_{ref} - \omega_{act}$$

$$\Delta e(k) = e(k) - e(k-1)$$

$$u(k) = u(k-1) + \Delta u(k)$$

Control knowledge or experience of an expert is expressed as a set of fuzzy IF-Then rules of the form:

$$\text{IF } e \text{ is } A_i \text{ and } \Delta e \text{ is } B_i \text{ THEN } U_f \text{ is } Z_i \tag{9}$$

where, $i = 1, 2, 3, ..., m$

There are seven fuzzy sets for each linguist value { A_i, B_i, Z_i }. These are NB(Negative Big), NM(Negative Medium), NS(Negative Small), ZO(Zero), PS(Positive Small), PM(Positive Medium), PB(Positive Big). And 49 fuzzy control rules are designed for two inputs and one output fuzzy system U_f. A maximum of four rules will be active at any time[8].

$$\mu_Z(U_f) = \max_{(j=i,i+1)} \min(\min(\mu_{A_j}(e), \mu_{B_j}(\Delta e)), \mu_{Z_j}(U_f)) \tag{10}$$

$$\mu(U_i) = (\mu_{A_j}(e), \mu_{B_j}(\Delta e))$$

$$\mu_Z(U_f) = \max_{(j=i,i+1)} \min(\min(\mu(U_i), \mu_{Z_j}(U_f)) \tag{11}$$

After that, defuzzifier converts Eq. (9) into the following expression:

$$U_f = \frac{\sum_{i=1}^{n} \mu(U_i \cdot C_i)}{\sum_{i=1}^{n} \mu(U_i)} \tag{12}$$

where, $\mu(U_i)$ is the values of membership function (MF) for output and C_i is the values of output MFs centers. Next this result is transferred to the BLDC motor of AGV.

Fuzzy PID controller Design

Conventional PID control technique is widely used in application field. Assume that k_{p0}, k_{i0}, k_{d0} are initial gain, integral coefficient and derivate coefficient. In conventional method, initial parameters are determined by experience and they don’t change in control process. The output of conventional PID is expressed as:

$$u(t) = k_{p0}e(t) + k_{i0}\int e(t)dt + k_{d0}\frac{de(t)}{dt} \tag{13}$$

where, $e(t) = \omega_{ref} - \omega(t)$ and $\omega(t)$ is current speed of BLDCM at time t. ω_{ref} is speed reference value of BLDCM, $e(t)$ is difference between current speed and reference value. As mentioned above, coefficients of conventional PID never change all the time, therefore this control method isn’t suitable for some processes with nonlinearity and cannot avoid influence of sudden change[16,19]. Fuzzy PID control is combination of fuzzy logic and PID control, it reveals high control performance before specific objects with nonlinearity or parameter uncertainty. PID coefficients after passing FPID are expressed as:

$$\begin{cases} k_p = k_{p0} + \Delta k_p \\ k_i = k_{i0} + \Delta k_i \\ k_d = k_{d0} + \Delta k_d \end{cases} \tag{14}$$

In this paper, we propose fuzzy PID controller of speed control system of BLDCM, in which the error value e and error change Δe are inputs and Δk_p, Δk_i, Δk_d are outputs. We take the fuzzy subset of fuzzy language variables of inputs are NB, NS, ZE, PS, PB, representing a negative large, negative small, zero, positive small and positive large respectively. Output language variables are NB, NM, NS, ZO, PS, PM PB, representing a negative large, negative medium, negative small, zero, positive small, positive medium and positive large respectively. Inputs and outputs are selected Gaussian membership functions and k_e and k_{ec} are quantized (-0.2, 0.2), (-0.05, 0.05), (-2,2) region.

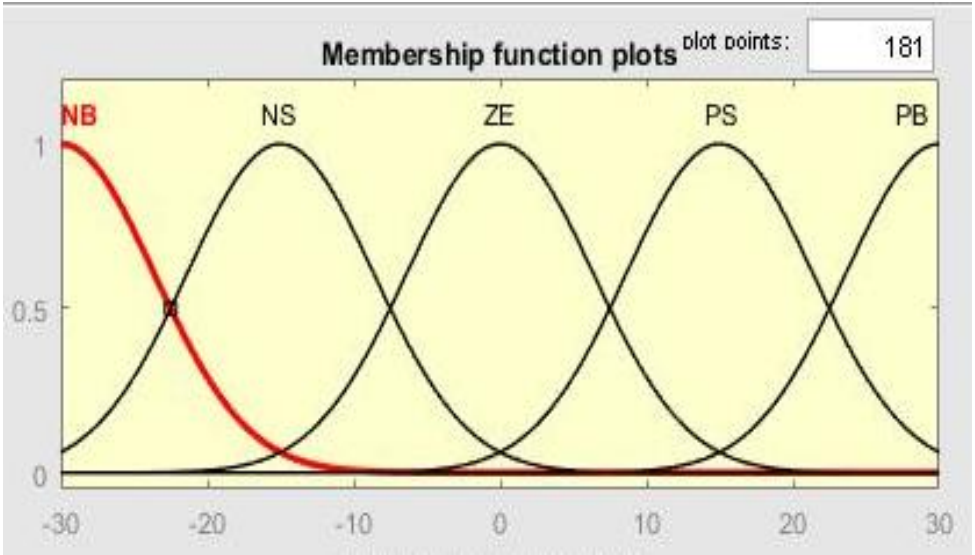

Fig.1 The membership functions of error

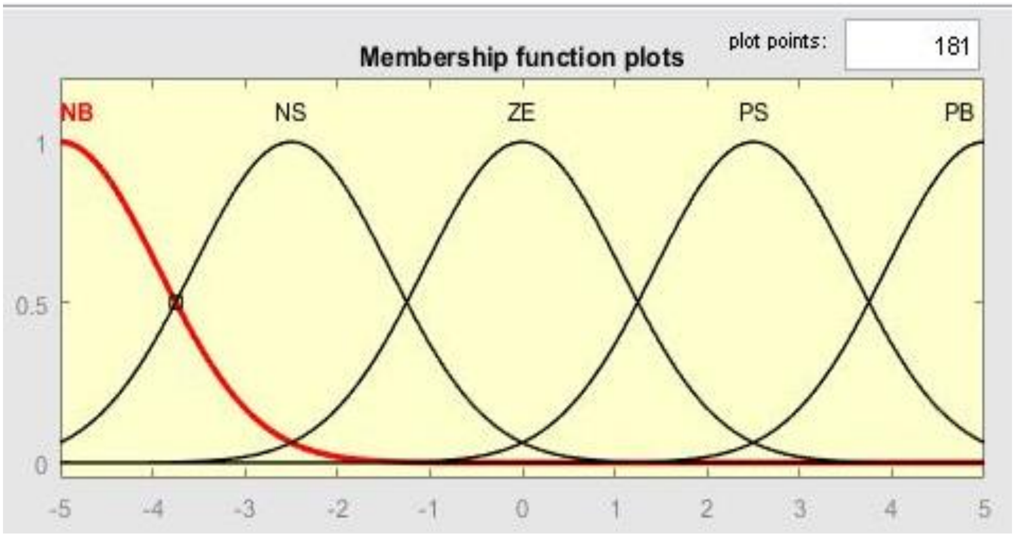

Fig.2 The membership functions of error change

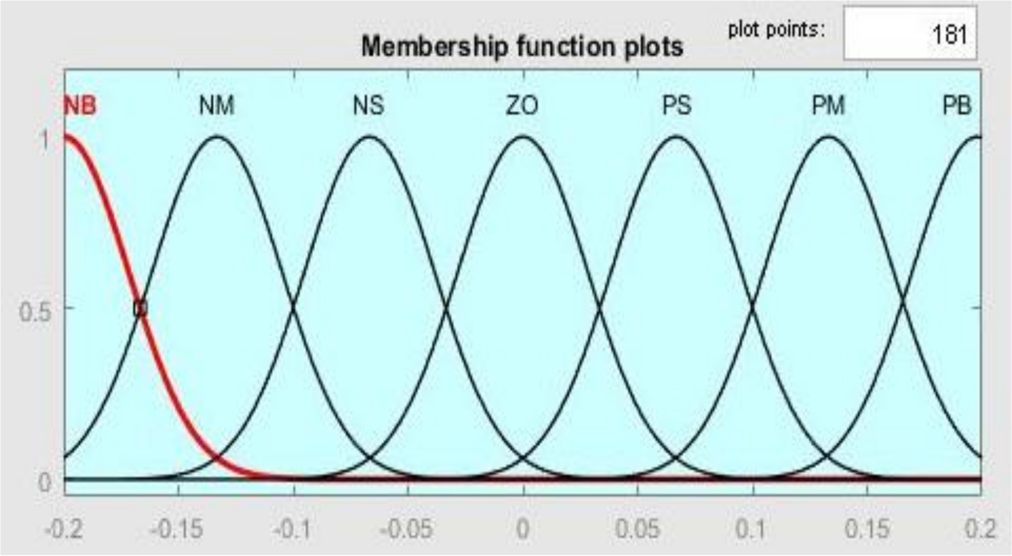

Fig.3 The membership functions of Δk_p

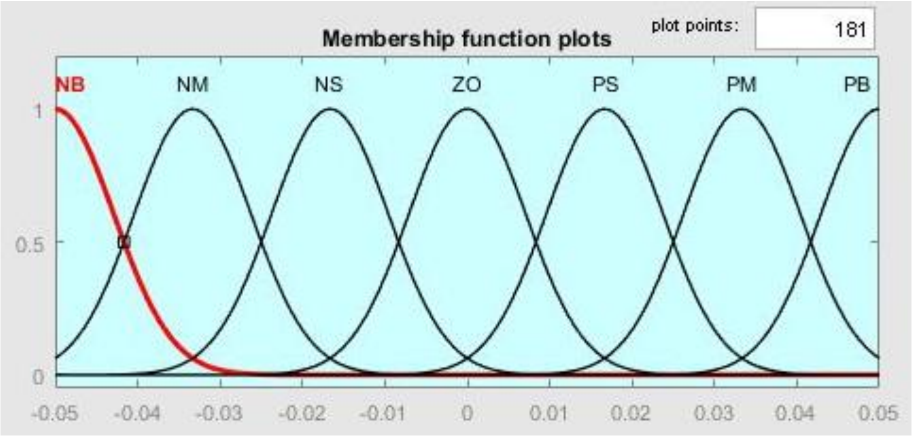

Fig.4 The membership functions of Δk_i

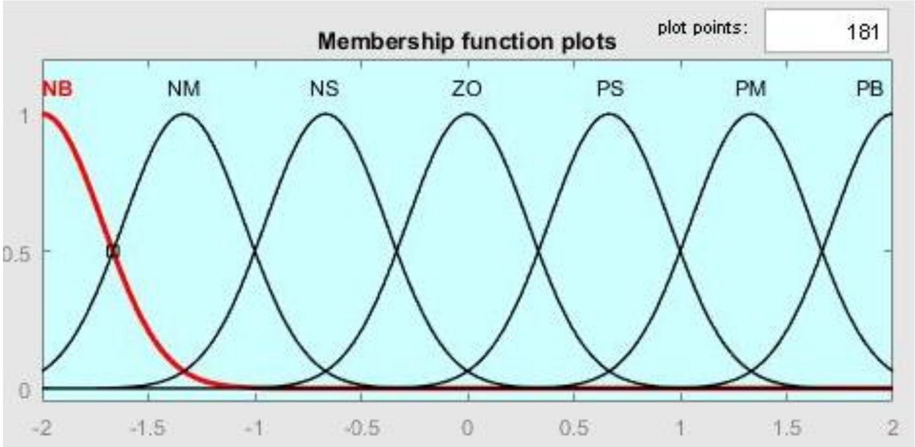

Fig.5 The membership functions of Δk_d

Based on knowledge and experience of an expert about control object, fuzzy control rules are made.

Table 1 Fuzzy rule table of Δk_d , Δk_d and Δk_d

ec	e						
	NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	NB PB PS	NB PB PS	NB PB PS	PB NB ZB	PB NB ZO	PB NM ZO	ZE ZE PS
NM	NM PM PS	NB PM PM	NS PS PM	PM NM ZO	PM NM PS	PM NM NS	ZE PM PS
NS	PB NB NB	PM NS NB	NS PS ZE	PS ZO NS	ZO ZO ZO	ZO PS NS	PS PS NM
ZO	PS NS NB	PS PS NM	ZO ZO NS	PS NS NB	PS NS NS	PS NS PS	PS NS ZO
PS	PS NS NB	NS PS NM	NS PS NS	NS PS ZO	NS PS ZE	PS ZO NM	PM NS ZO

PM	PS NS NB	NS PM NM	NS PS NS	PB ZO NM	NS PM ZO	PM ZO NM	PM NS NM
PB	PB PS NM	PB NM PM	NS PS ZE	PB NB ZO	PB NB ZE	PB NB NS	PB NM NB

Fuzzy PID control system is as follows.

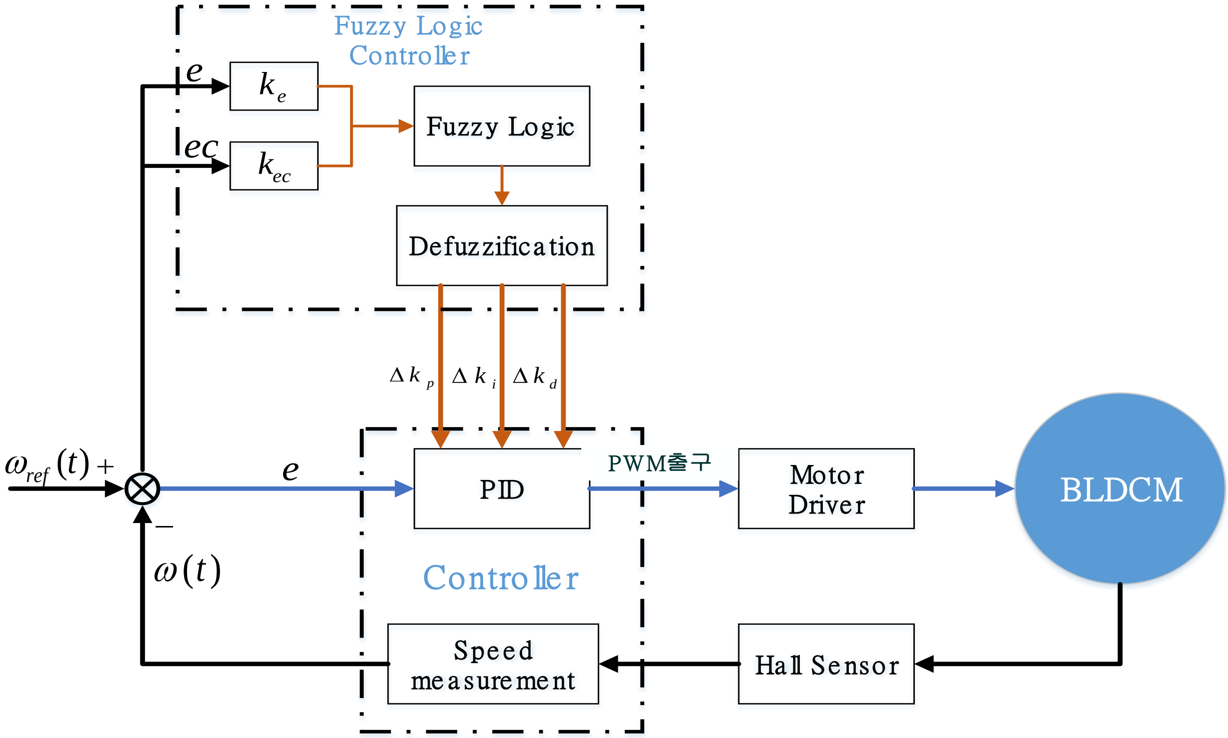

Fig.6 Fuzzy PID speed control system of BLDCM

Simulation results

Based on Matlab/Simulink establish a model of BLDC control system, and the model simulate BLDCM speed control system. The basic use of system simulation module in MATLAB/Simulink built in a fuzzy PID controller and conventional PID simulation model, before simulation the first edited embedded fuzzy inference system Fuzzy Logic Controller module.

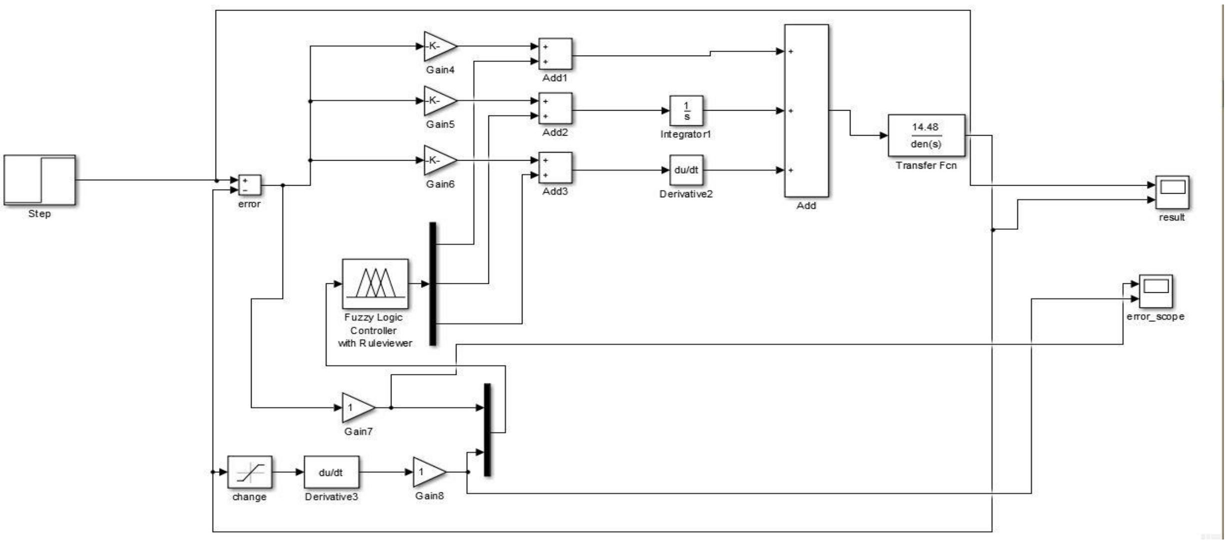

Fig.7 Simulation frame diagram of control system using MATLAB/Simulink

The simulated results of the speed control system of the BLDC motor based on two controllers: conventional PID and Fuzzy PID are shown in Figs. 8-13. Fig. 8 shows speed tracking of two controller s at speed 350rpm. The speed response, current change and moment change of BLDCM at speed 300rpm and 600rpm under varying load condition are shown in Fig. 9-13.

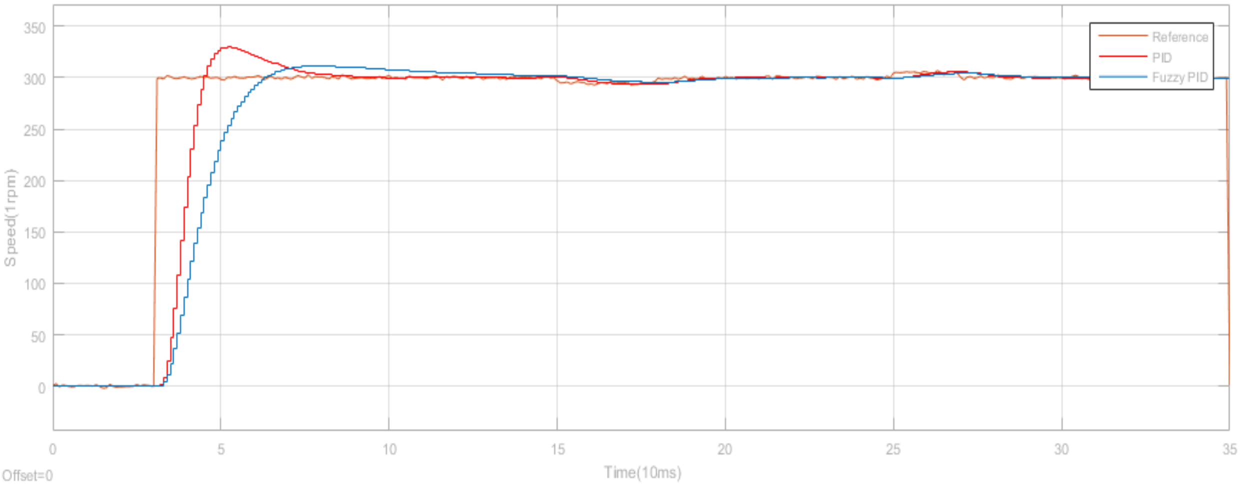

Fig8. Speed tracking of two controllers: conventional PID and proposed one

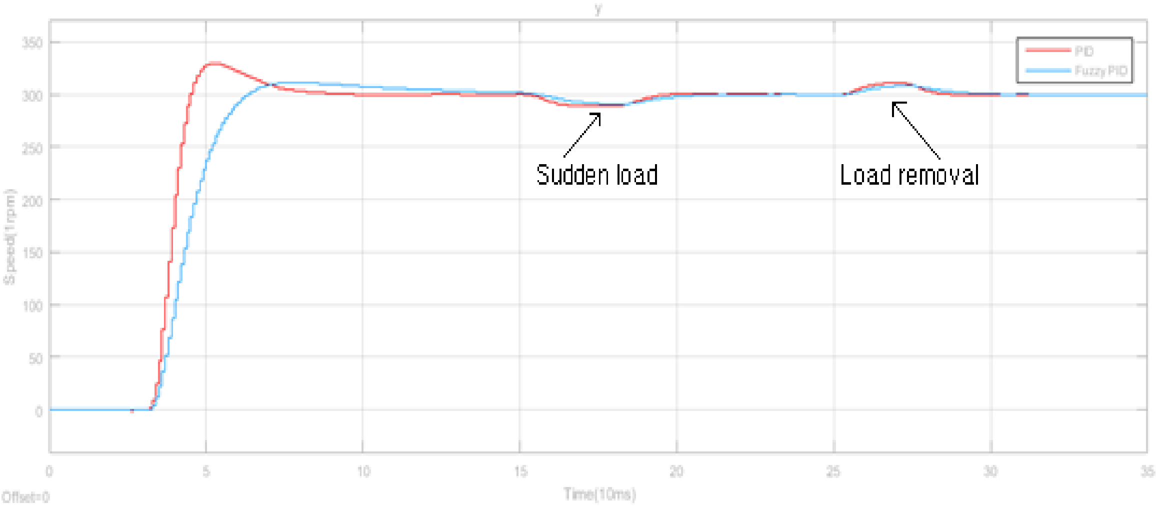

Fig.9 Speed response at speed 300rpm under varying load condition

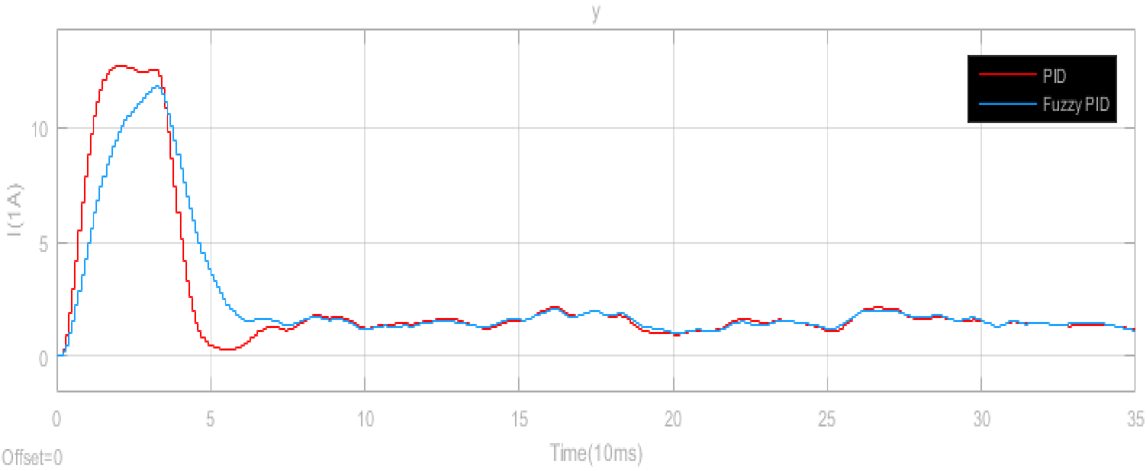

Fig.10 Current change at speed 300rpm with sudden load

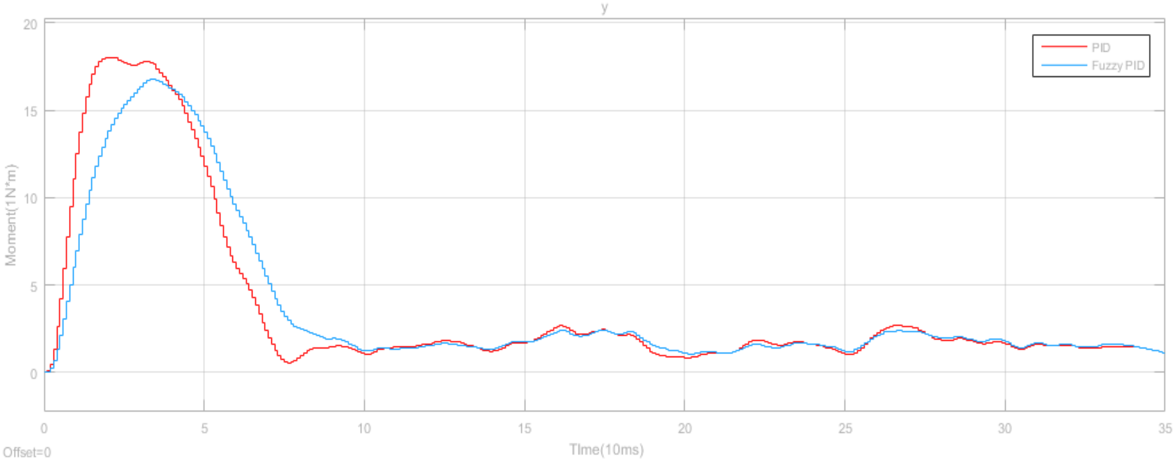

Fig.11 Moment change at speed 300rpm with sudden load

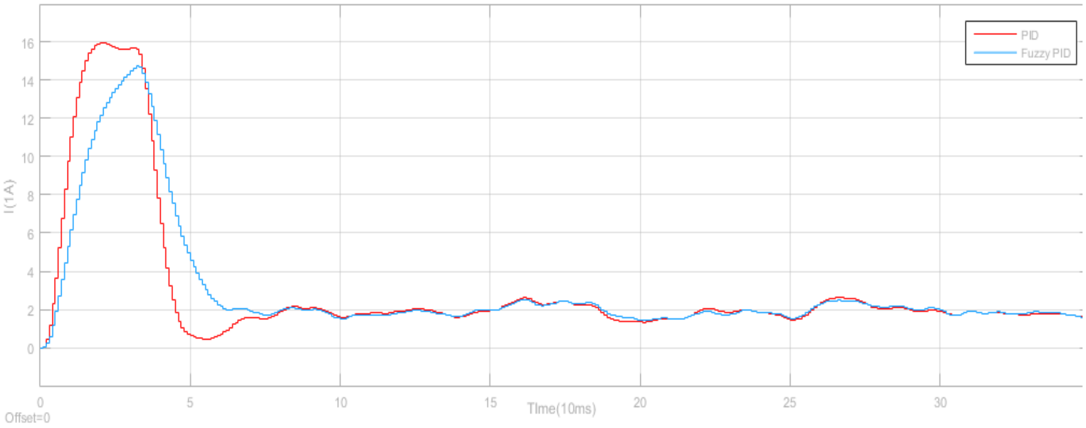

Fig.12 Current change at speed 600rpm with sudden load

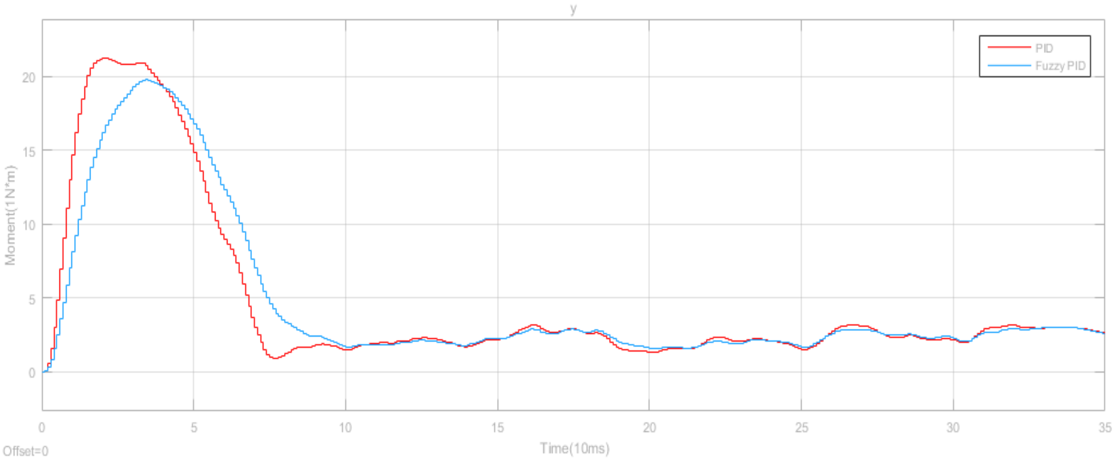

Fig.13 Moment change at speed 600rpm with sudden load

These figures show that proposed FPID controller is better than conventional PID with small overshoot and fast response. Moreover, it is reliable under speed change and sudden load conditions.

Hardware Implementation of AGV

After simulating BLDCM control system using MATLAB/Simulink, we introduced it into BLDCM of Automatic Guided Vehicle(AGV) and made field test. This AGV is inductive wire following robot and the drive wheel is BLDCM. Characteristics of this AGV is as following table.

Table 2 Technical specifications of AGV

Specification	Value
Load capacity	Below 200kg
Navigation way	Line following/Zigbee
Control method	Button/Zigbee
Rated speed	0.6m/s
Maximum speed	1.2m/s
Walking Direction	Forward, Backward
Minimum turning radius	1.3m
Noise level	Below 40dB
Power supply	48V Battery
Drive wheel	Two BLDC motors

Fig.14 AGV for transportation

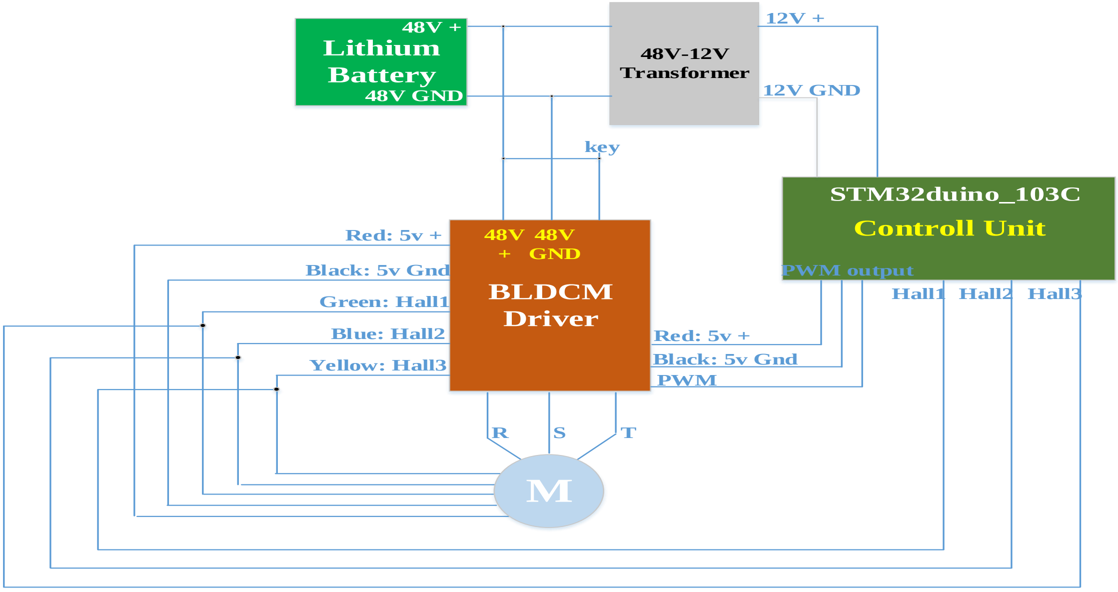

Fig.15 Control circuit diagram of AGV

Fig.15 is control circuit diagram of AGV. 48V Lithium battery supply power to control board with Arduino controller, motor drivers and other units such as relays and buttons after passing through 48V-12V transformer. Hall sensor signals from motor is connected to driver and control board to measure current speed simultaneously.

CONCLUSION

This paper presents an improved speed control system of BLDCM for AGV. We measure current speed of the robot using Hall-effect sensor of BLDCM and designed and implemented Fuzzy PID control system to improve speed response and robustness of the speed control system of AGV. Simulations were made with two controllers: conventional PID and FPID. Results show that proposed method satisfy control requirement of the AGV.

In the future, we will focus on improving accuracy and reliability of speed control system of BLDCM which are widely used in application fields.

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Conflict of interests

The author declares no conflict of interest.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data Availability

The data that support the findings of this study are available within the article.

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