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# Optimal Tuning of PI-like Fuzzy Controller Using Variable Membership Function's Slope

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## 1. Introduction

As the speed controlled BLDC motor drive systems are increasingly employed in the industrial drive systems, the various requirements for the performance of such systems become severe. In this investigation, we employ a simple and natural method to design a controller to control the BLDC motor drive system, which is so-called Takagi-Sugeno fuzzy model [1].

Recently, there have been a lot of researches in the Takagi-Sugeno fuzzy model [2], [3], [4]. They offer a systematic procedure to design controllers of BLDC motor drive systems. Servo motor position controller using the fuzzy control algorithm has been developed by Li and Lau [15], and they discuss the steady-state error, settling time, and response time. According to their paper, the performance of the fuzzy controller is better than that of the conventional PI controller and as good as that of the Model Reference Adaptive Control. We do not think a general method can be found to obtain optimum values for fuzzy controllers, because any optimum values always depend on specific models of the process and the control objectives. So, tuning fuzzy controllers must be done based on experts' knowledge of the controlled plant, not by computation.

In this paper, our objective is to prescribe a methodology for tuning fuzzy controllers, and this paper presents a scheme for obtaining optimum values of fuzzy membership function's slope. In other words, an optimal slope is sought by evaluating various fuzzy membership function's slope values. With this information, you can tune your fuzzy control systems easier and faster, also of course based on your knowledge of the controlled plant.

This paper is organized as follows. A brief description of the used fuzzy system are presented in Section 2. Section 3 presents fuzzy membership functions. Simulation results are presented in Section 4 with setup of the BLDC motor drive system. Section 5 concludes this paper.

## 2. Used fuzzy systems

The used fuzzy logic system is a zero-order Takagi-Sugeno fuzzy system which performs a mapping from an input vector  $z = [z_1 \ \cdots \ z_m] \in \Omega_z \subset \mathbb{R}^m$  to a scalar output variable  $y_f \in \mathbb{R}$ , where  $\Omega_z = \Omega_{z_1} \times \cdots \times \Omega_{z_m}$  and  $\Omega_{z_i} \subset \mathbb{R}$ . If we define  $M_i$  fuzzy sets  $F_i^j$ ,  $j = 1, \dots, M_i$ , for each

input  $z_i$ , then the fuzzy system will be characterized by a set of if-then rules of the form[5,14]

$$R^k : \text{If } z_1 \text{ is } G_1^k \text{ and...and } z_m \text{ is } G_m^k$$

$$\text{Then } u \text{ is } u^k \quad (k=1, \dots, N) \quad (1)$$

where  $G_i^k \in \{F_i^1, \dots, F_i^{M_i}\}$ ,  $i=1, \dots, n$ ,  $y^k$  is the crisp output of the  $k$ -th rule, and  $N$  is the total number of rules.

The FLC can operate either on the actual universes of discourse or on the normalized universes of discourse of the variables. In case of operating on the actual universe of discourse, the FLC has three main stages, as shown in Fig. 7, which are:

1. *Fuzzification*, a process of producing a fuzzy input on the base of a crisp one.
2. *Inference engine and rule-base*, a process of transforming fuzzy input into a fuzzy output by dealing with fuzzy rules and as a result the response corresponding to the inputs is produced.
3. *Defuzzification*, a process of producing a crisp output on the base of a fuzzy one.

However, in case of operating on the normalized universe of discourse, we add two more stages - one before fuzzification and one after defuzzification -, which are:

1. *Normalization*, a process of mapping the actual value of the input variable to the normalized space of the same variable.
2. *Denormalization*, a process of mapping the normalized value of the output control signal to the actual space of the same output control signal.

By using the singleton fuzzifier, product inference engine, and center-average defuzzifier, the final output of the fuzzy system is given as follows [5]:

$$u_l(z) = \frac{\sum_{k=1}^N \mu_k(z) y^k}{\sum_{k=1}^N \mu_k(z)} \quad (2)$$

where

$$\mu_k(z) = \prod_{i=1}^m \mu_{G_i^k}(z_i) \quad \text{with } \mu_{G_i^k} \in \{\mu_{F_i^1}, \dots, \mu_{F_i^{M_i}}\}$$

where  $\mu_{F_i^j}(x_i)$  is the membership function of the fuzzy set  $F_i^j$ .

By introducing the concept of fuzzy basis function [5], the output given by Eq. (2) can be rewritten in the following compact form:

$$u(z) = w^T(z) \theta \quad (3)$$

where  $\theta = [w^1, \dots, w^N]^T$  is a vector grouping all consequent parameters, and

$w(z) = [w_1(z), \dots, w_N(z)]^T$  is a set of fuzzy basis functions defined as

$$w_k(z) = \frac{\mu_k(z)}{\sum_{i=1}^N \mu_i(z)}, \quad k=1, \dots, N$$

The fuzzy system (3) is assumed to be well defined so that  $\sum_{i=1}^N \mu_j(z) \neq 0$  for all  $z \in \Omega_z$ .

The fuzzy system (3) is a universal approximator of continuous functions over a compact set if its parameters are suitably selected [5].

#### 4. Membership function and slope

In practical control applications, the triangular membership function is generally selected for representing fuzzy sets. Because, in term of real-time requirements by the inference engine, their parametric, functional description of membership function can be easily obtained, stored with minimal use of memory, and manipulated efficiently [11].

A triangular membership function is described by three parameters  $a$ ,  $b$  and  $c$  and given by the expression

$$f(x, a, b, c) = \max \left\{ \min \left( \frac{x-a}{b-a}, \frac{c-x}{c-b} \right), 0 \right\} \quad (4)$$

where the parameters  $a$  and  $c$  locate the "feet" of the triangle and the parameter  $b$  locates the peak, as shown in Fig. 1

We confine our discussion to a PI like fuzzy controller with triangle membership functions. PI-like fuzzy controllers are so named because their inputs and outputs are equivalent to traditional PI controllers. In a PI-like fuzzy controller, the following parameters can be tuned.

*SCALING FACTORS* of IF-part/THEN-part fuzzy variables. We define a scaling factor as the maximum peak value, which defines the universe of discourse of the fuzzy variable (Fig. 2).

*PEAK VALUE* : the value at which the membership function is 1.0 (Fig. 2).

*WIDTH VALUE* : the interval from the peak value to the point at which membership becomes 0.0 (Fig. 2).

We define the membership functions with equal-interval peak values shown in Fig. 2 as standard membership functions. When the standard membership functions are used on a PI-like fuzzy controller, the relationship between output  $\mu$  (membership value) and input  $x$  (crisp value) can be expressed approximately as follows: ( $d$  = width value)

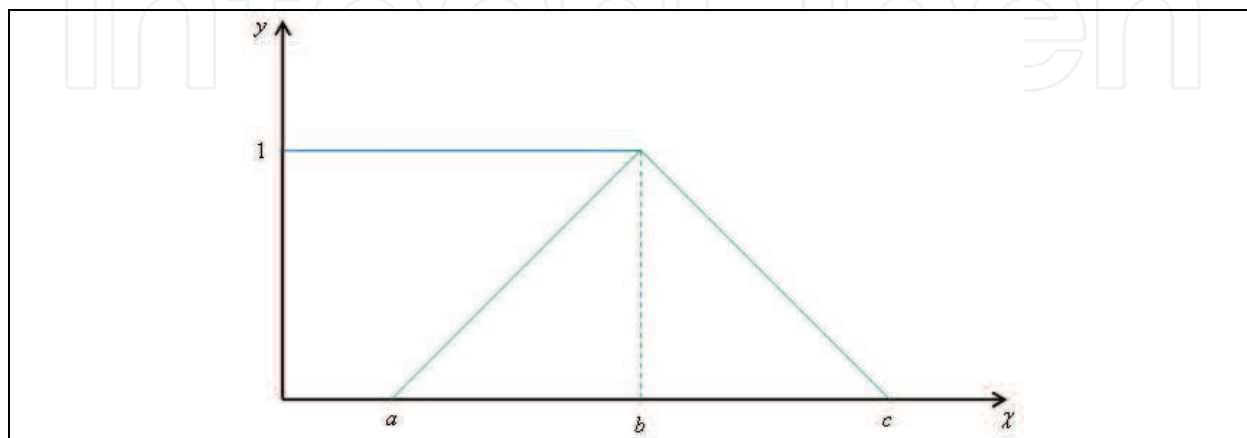


Fig. 1. Triangular Membership Function

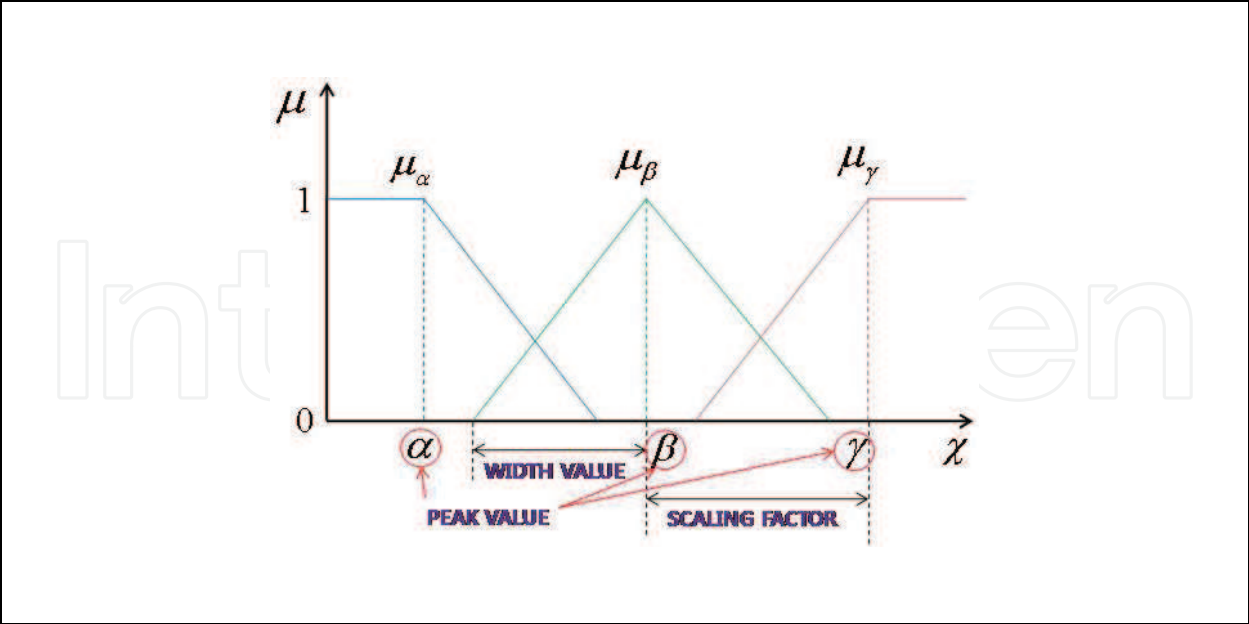


Fig. 2. Scaling Factor of a Membership Function

$$\mu_{\alpha} = 1$$

$$\mu_{\beta} \Rightarrow \begin{cases} \text{if } \frac{1}{d} \leq \beta - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \beta - x \text{ then } 1 - (\beta - x)d \end{cases}$$

$$\mu_{\gamma} \Rightarrow \begin{cases} \text{if } \frac{1}{d} \leq \gamma - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \gamma - x \text{ then } 1 - (\gamma - x)d \end{cases}$$

if  $x \leq a$  then

$\left\{ \begin{array}{l} \mu_{\alpha} = 1 \\ \mu_{\beta} \Rightarrow \begin{cases} \text{if } \frac{1}{d} \leq \beta - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \beta - x \text{ then } 1 - (\beta - x)d \end{cases} \\ \mu_{\gamma} \Rightarrow \begin{cases} \text{if } \frac{1}{d} \leq \gamma - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \gamma - x \text{ then } 1 - (\gamma - x)d \end{cases} \end{array} \right.$

$$\mu_{\alpha} = \begin{cases} \text{if } \frac{1}{d} \leq x - \alpha \text{ then } 0 \\ \text{if } \frac{1}{d} > x - \alpha \text{ then } 1 - (x - \alpha)d \end{cases}$$

$$\mu_{\beta} = \begin{cases} \text{if } \frac{1}{d} \leq \beta - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \beta - x \text{ then } 1 - (\beta - x)d \end{cases}$$

$$\mu_{\gamma} = \begin{cases} \text{if } \frac{1}{d} \leq \gamma - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \gamma - x \text{ then } 1 - (\gamma - x)d \end{cases}$$

if  $\alpha < x \leq \beta$  then

$\left\{ \begin{array}{l} \mu_{\alpha} = \begin{cases} \text{if } \frac{1}{d} \leq x - \alpha \text{ then } 0 \\ \text{if } \frac{1}{d} > x - \alpha \text{ then } 1 - (x - \alpha)d \end{cases} \\ \mu_{\beta} = \begin{cases} \text{if } \frac{1}{d} \leq \beta - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \beta - x \text{ then } 1 - (\beta - x)d \end{cases} \\ \mu_{\gamma} = \begin{cases} \text{if } \frac{1}{d} \leq \gamma - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \gamma - x \text{ then } 1 - (\gamma - x)d \end{cases} \end{array} \right.$

(5)

$$\mu_{\alpha} = \begin{cases} \text{if } \frac{1}{d} \leq x - \alpha \text{ then } 0 \\ \text{if } \frac{1}{d} > x - \alpha \text{ then } 1 - (x - \alpha)d \end{cases}$$

$$\mu_{\beta} = \begin{cases} \text{if } \frac{1}{d} \leq \beta - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \beta - x \text{ then } 1 - (\beta - x)d \end{cases}$$

$$\mu_{\gamma} = \begin{cases} \text{if } \frac{1}{d} \leq \gamma - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \gamma - x \text{ then } 1 - (\gamma - x)d \end{cases}$$

if  $\alpha < x \leq \beta$  then

$\left\{ \begin{array}{l} \mu_{\alpha} = \begin{cases} \text{if } \frac{1}{d} \leq x - \alpha \text{ then } 0 \\ \text{if } \frac{1}{d} > x - \alpha \text{ then } 1 - (x - \alpha)d \end{cases} \\ \mu_{\beta} = \begin{cases} \text{if } \frac{1}{d} \leq \beta - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \beta - x \text{ then } 1 - (\beta - x)d \end{cases} \\ \mu_{\gamma} = \begin{cases} \text{if } \frac{1}{d} \leq \gamma - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \gamma - x \text{ then } 1 - (\gamma - x)d \end{cases} \end{array} \right.$

(6)

$$\text{if } \beta < x \leq \gamma \text{ then } \left\{ \begin{array}{l} \mu_{\alpha} = \begin{cases} \text{if } \frac{1}{d} \leq x - \alpha \text{ then } 0 \\ \text{if } \frac{1}{d} > x - \alpha \text{ then } 1 - (x - \alpha)d \end{cases} \\ \mu_{\beta} = \begin{cases} \text{if } \frac{1}{d} \leq x - \beta \text{ then } 0 \\ \text{if } \frac{1}{d} > x - \beta \text{ then } 1 - (\beta - x)d \end{cases} \\ \mu_{\gamma} = \begin{cases} \text{if } \frac{1}{d} \leq \gamma - x \text{ then } 0 \\ \text{if } \frac{1}{d} > \gamma - x \text{ then } 1 - (\gamma - x)d \end{cases} \end{array} \right. \quad (7)$$

$$\text{if } \gamma < x \text{ then } \left\{ \begin{array}{l} \mu_{\alpha} = \begin{cases} \text{if } \frac{1}{d} \leq x - \alpha \text{ then } 0 \\ \text{if } \frac{1}{d} > x - \alpha \text{ then } 1 - (x - \alpha)d \end{cases} \\ \mu_{\beta} = \begin{cases} \text{if } \frac{1}{d} \leq x - \beta \text{ then } 0 \\ \text{if } \frac{1}{d} > x - \beta \text{ then } 1 - (\beta - x)d \end{cases} \\ \mu_{\gamma} = 1 \end{array} \right. \quad (8)$$

where  $d$  is membership function's slope

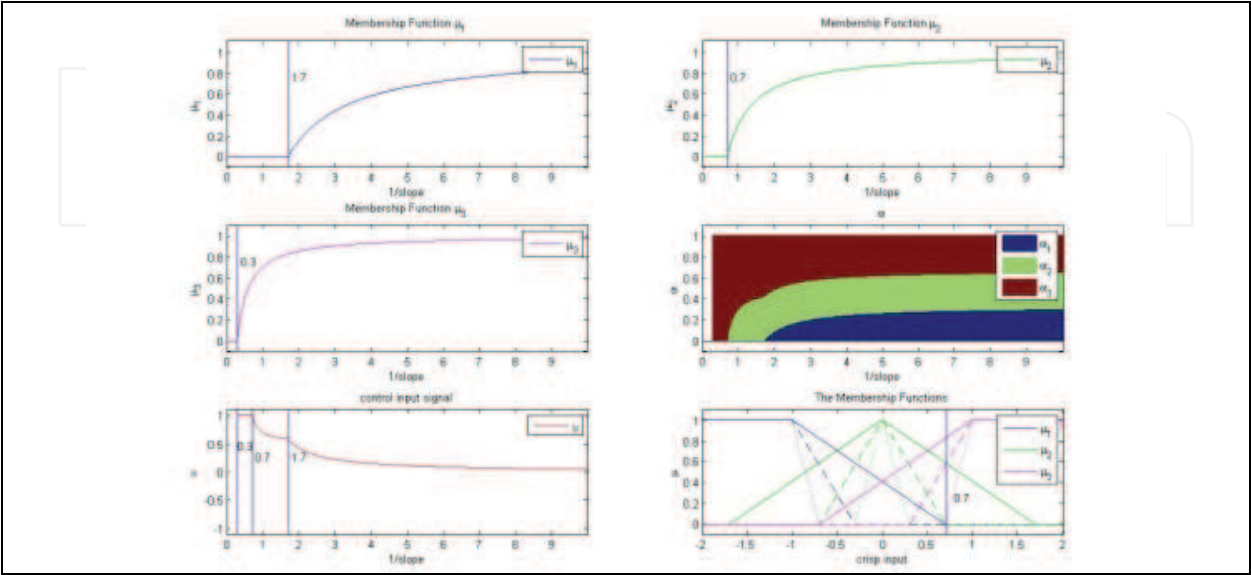


Fig. 3. Different Slopes

$$w_{\alpha} = \frac{\mu_{\alpha}}{\mu_{\alpha} + \mu_{\beta} + \mu_{\gamma}}, \quad w_{\beta} = \frac{\mu_{\beta}}{\mu_{\alpha} + \mu_{\beta} + \mu_{\gamma}}, \quad w_{\gamma} = \frac{\mu_{\gamma}}{\mu_{\alpha} + \mu_{\beta} + \mu_{\gamma}} \tag{9}$$

$$u = \frac{\mu_{\alpha}\alpha + \mu_{\beta}\beta + \mu_{\gamma}\gamma}{\mu_{\alpha} + \mu_{\beta} + \mu_{\gamma}} = w_{\alpha}\alpha + w_{\beta}\beta + w_{\gamma}\gamma \tag{10}$$

5. Simulation results

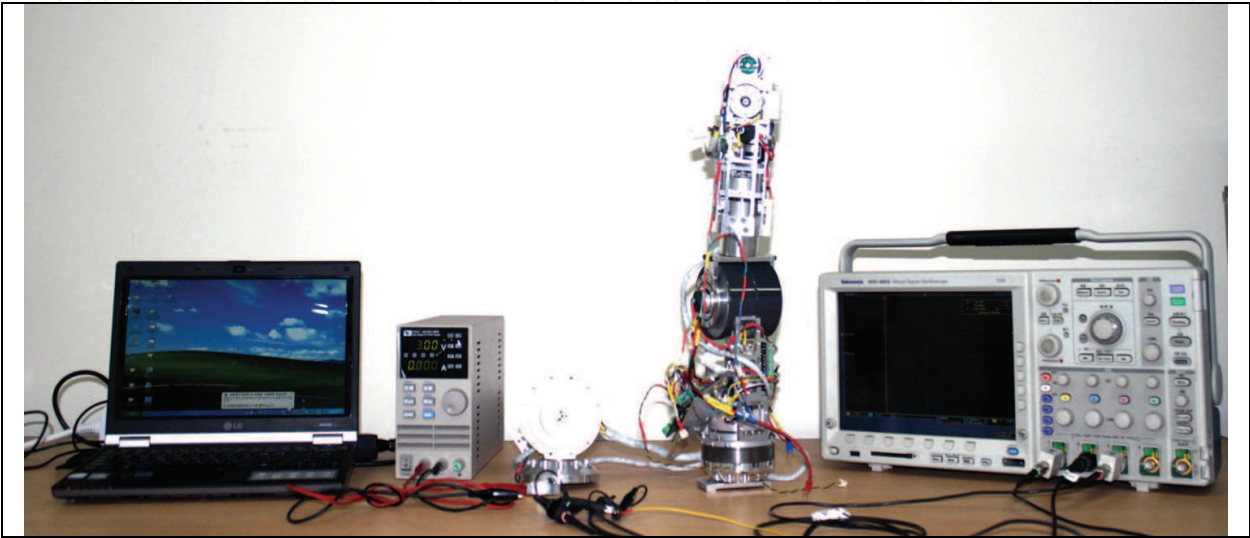


Fig. 4. BLDC Test Platform

3.1 Control system setup

We will assume the following values for the physical parameters. These values were derived by Maxon Motor Catalog.

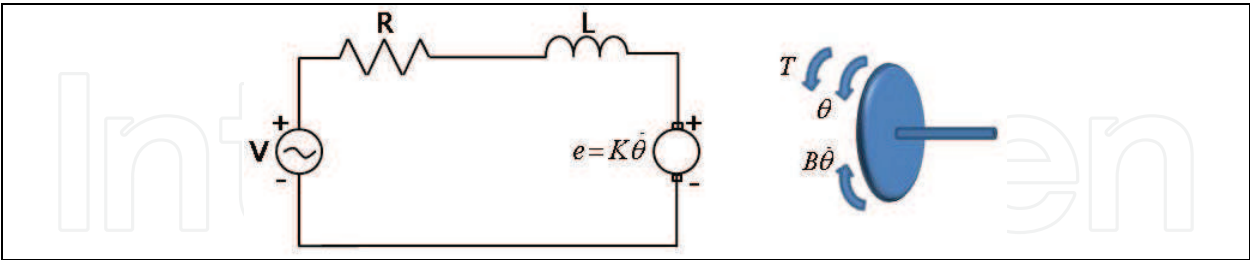


Fig. 5. The electric circuit of the armature and the free body diagram of the rotor.

The motor torque,  $T(t)$ , is related to the armature current,  $i$ , by a constant factor  $K_T$ .  $T_L(t)$  is load torque. The back emf,  $e$ , is related to the rotational velocity by the following equations:

$$T(t) = K_T i \tag{11}$$
$$e = K_e \dot{\theta}$$

In SI units (which we will use),  $K_T$  (armature constant) is equal to  $K_e$  (motor constant).



From the figure above we can write the following equations based on Newton's law combined with Kirchhoff's law:

$$J\ddot{\theta} - B\dot{\theta} = K_T i$$

$$L \frac{di}{dt} + Ri = V - K_e \dot{\theta} \quad (12)$$

Using Laplace Transforms, the above modeling equations can be expressed in terms of  $s$

$$s(Js + B)\theta(s) = K_T I(s)$$

$$(Ls + R)I(s) = V - K_s \theta(s)$$

By eliminating  $I(s)$  we can get the following open-loop transfer function, where the rotational speed is the output and the voltage is the input.

$$\frac{\dot{\theta}}{V} = \frac{K}{(Js + B)(Ls + R) + K^2} \quad (13)$$

In the state-space form, the equations above can be expressed by choosing the rotational speed and electric current as the state variables and the voltage as an input. The output is chosen to be the rotational speed.

$$\frac{d}{dt} \begin{bmatrix} \dot{\theta} \\ i \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & \frac{K}{J} \\ -\frac{K}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} V \quad (14)$$

$$\dot{\theta} = [1 \quad 0] \begin{bmatrix} \dot{\theta} \\ i \end{bmatrix}$$

And, the block diagram of BLDC motor drive system is shown in Fig.6.

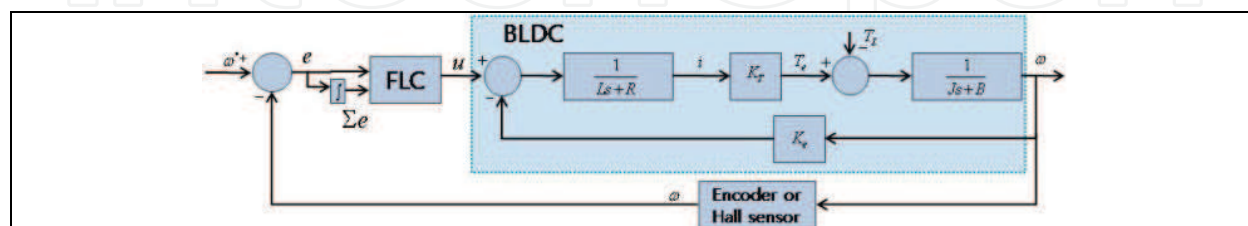


Fig. 6. The block diagram of BLDC motors drive system.

Figure 7 shows the general structure of a FLC which accepts the input variables, process state variables, as crisp values and produce an output control signal, process input, also as crisp values [18]. The input variables are selected among:



- 1. Error signal, denoted by  $e$  ;
- 2. Sum of errors or error integral, denoted by  $\sum e$  ;

The output control signals are selected among:

- 3. Control output, denoted by  $u$  .

This controller describes with the aid of fuzzy if-then rules the relationship between the control output  $u(k)$  on the one hand, and the error  $e(k)$  and its sum  $\sum e(k)$  on the other hand as shown in Fig. 7.

$$u(k) = f[e(k), \sum e(k)]$$

This can be seen as a mapping of the pair  $e(k)$  and  $\sum e(k)$  to the corresponding control output  $u(k)$  .This is similar to the well-known conventional PI controller described by the equation:

$$u(k) = K_p e(t) + K_I \int_0^t e(t) dt$$

In the case of conventional PI controller, the relationship is linear, while in PI-like FLC it is nonlinear in general[18].

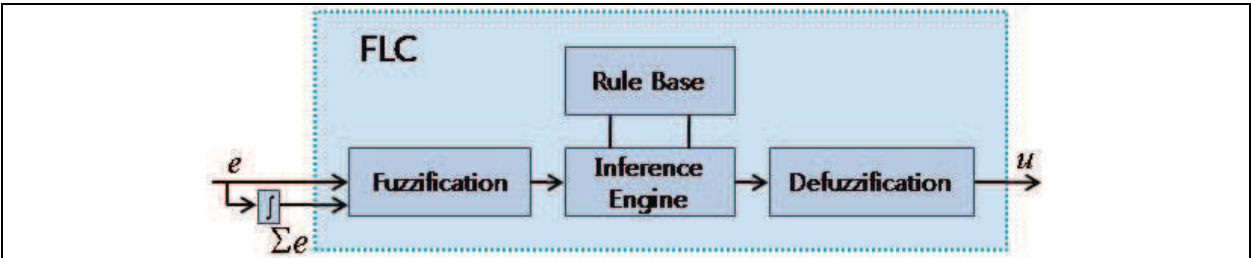


Fig. 7. The block diagram of a basic Fuzzy control system.

Specifications	Units
Number of poles	1
Moment of inertia, $J$	$0.00000512\text{ kg m}^2/\text{s}^2$
Viscous damping constant, $B$	$0.00057875\text{ Nms}$
Torque constant, $K_T$	$0.028\text{ Nm/Amp}$
Back-EMF constant, $K_e$	$0.028\text{ Nm/Amp}$
Armature inductance, $L$	$0.000186\text{ H}$
Terminal resistance, $R$	$1.35\text{ }\Omega$
Rated speed	$6540\text{ rpm}$
Rated torque	$0.088\text{ Nm}$
Rated current	$3.39\text{ A}$

Table 1. MOTOR RATINGS

3.2 B. Simulation results

$\mu_{\alpha_1}, \mu_{\alpha_2}$ 's slope	$\mu_{\beta_1}, \mu_{\beta_2}$ 's slope	$\mu_{\gamma_1}, \mu_{\gamma_2}$ 's slope		
		0.5	1	2
0.5	0.5	0.312	0.731	0.422
	1	0.296	0.1	0.116
	2	0.279	0.128	0.155
1	0.5	0.758	0.192	0.067
	1	0.103	0.065	0.066
	2	0.132	0.181	0.065
2	0.5	0.448	0.036	0.066
	1	0.114	0.036	0.066
	2	0.118	0.035	0.065

Table II. Settling time

Unit : second

	Sum of Error			
Error	$\sum_e^e$	$\mu_{\alpha}$	$\mu_{\beta}$	$\mu_{\gamma}$
	$\mu_{\alpha}$	0	0.3	0.6
	$\mu_{\beta}$	0.7	1	1.3
	$\mu_{\gamma}$	1.4	1.7	2

Table III. Rule Table

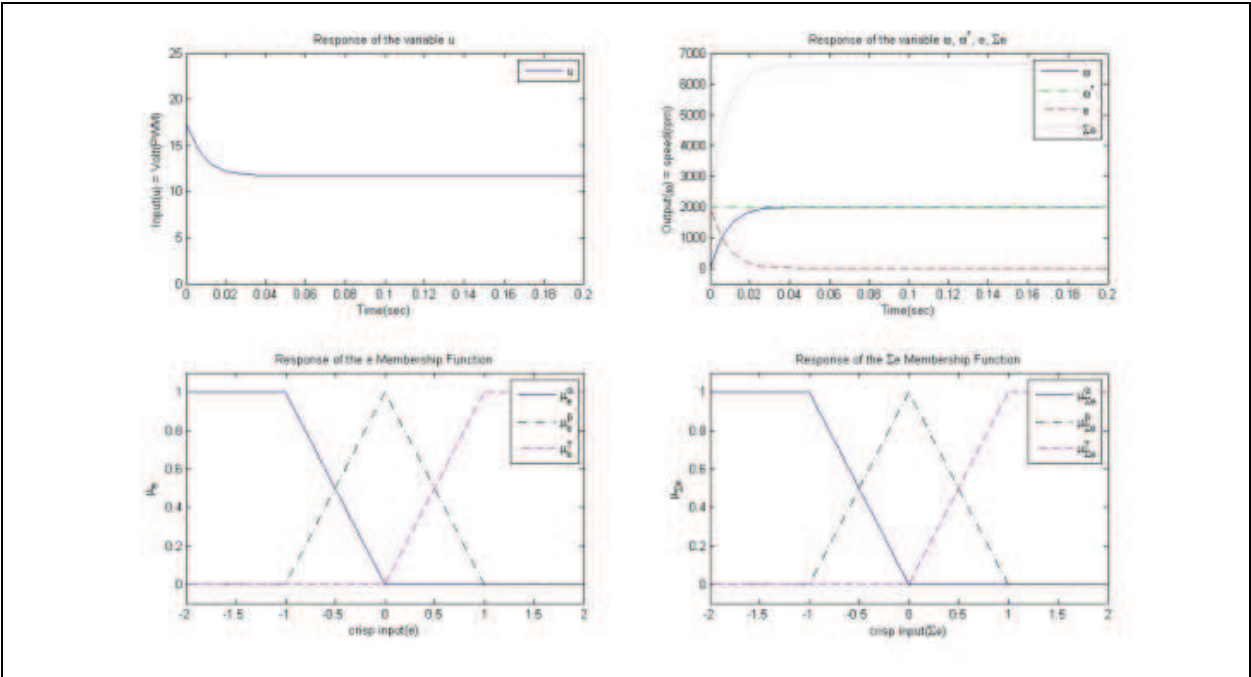


Fig. 8.  $\mu_e^{\alpha}$ ,  $\mu_{\Sigma e}^{\alpha}$ ,  $\mu_e^{\beta}$ ,  $\mu_{\Sigma e}^{\beta}$ ,  $\mu_e^{\gamma}$ ,  $\mu_{\Sigma e}^{\gamma}$  's slope = [1, 1, 1, 1, 1, 1]

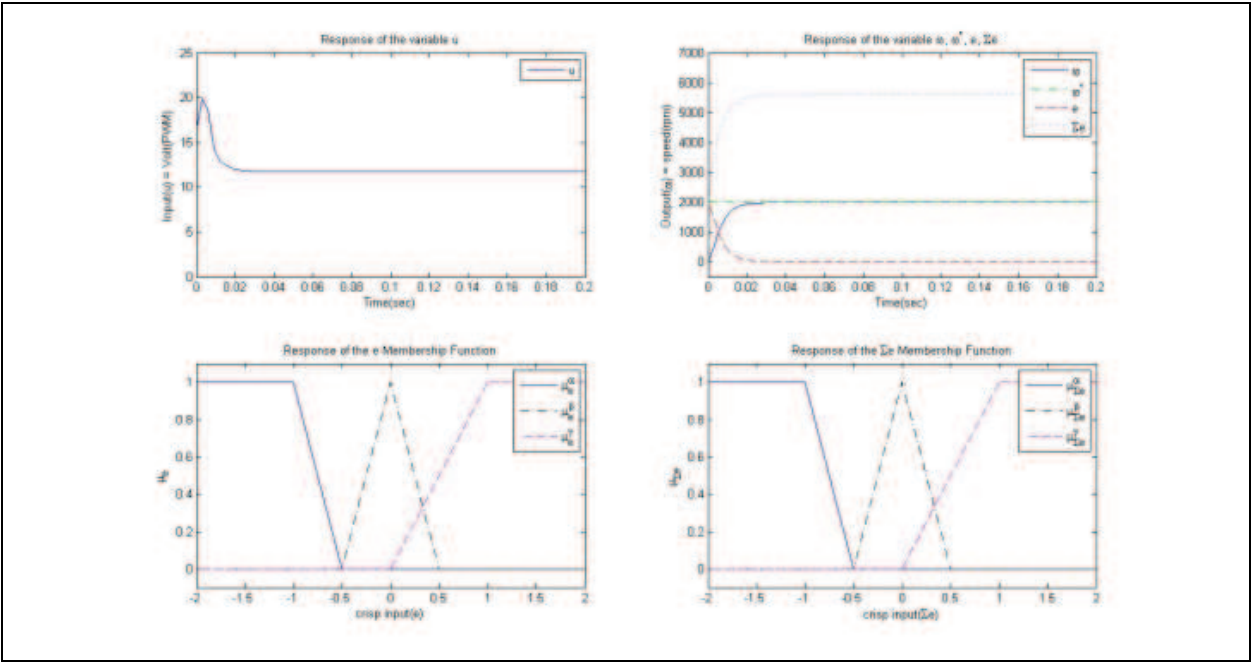


Fig. 9.  $\mu_e^{\alpha}$ ,  $\mu_{\Sigma e}^{\alpha}$ ,  $\mu_e^{\beta}$ ,  $\mu_{\Sigma e}^{\beta}$ ,  $\mu_e^{\gamma}$ ,  $\mu_{\Sigma e}^{\gamma}$  's slope = [2, 2, 2, 2, 1, 1]

6. Conclusions

This paper has focused on the effect of fuzzy membership function's slope for PI-like fuzzy control system. We use three membership functions to construct a fuzzy system. It was also proven that the fuzzy system guarantees that the output converged to the desired value. We

confirmed that increasing the slopes of the triangular membership functions (left and center) for fuzzifying the error and the sum of error can improve the starting and steady state performance of the BLDC motor drive system. It is also observed that changing of the slope of the membership functions (right) for fuzzifying the error and the sum of the error has a detrimental effect on the performance.

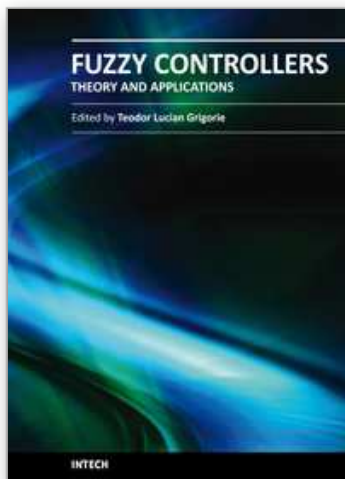
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Trying to meet the requirements in the field, present book treats different fuzzy control architectures both in terms of the theoretical design and in terms of comparative validation studies in various applications, numerically simulated or experimentally developed. Through the subject matter and through the inter and multidisciplinary content, this book is addressed mainly to the researchers, doctoral students and students interested in developing new applications of intelligent control, but also to the people who want to become familiar with the control concepts based on fuzzy techniques. Bibliographic resources used to perform the work includes books and articles of present interest in the field, published in prestigious journals and publishing houses, and websites dedicated to various applications of fuzzy control. Its structure and the presented studies include the book in the category of those who make a direct connection between theoretical developments and practical applications, thereby constituting a real support for the specialists in artificial intelligence, modelling and control fields.

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