Mathematical modelling and Speed control of a Sensored Brushless DC motor using Intelligent controller

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Abstract—**Brushless DC motor are rapidly gaining popularity due to its high efficiency and accurate control characteristics . For any industrial and domestic application it is necessary to control the speed accurately. The drawbacks of the conventional PID controllers for the speed control can be minimized using Fuzzy PID controller. This paper aims at the design of Fuzzy PID controller for a BLDC motor inorder to dynamically update the parameters of PID controller. The mathematical modelling of the motor along with the controller is derived for the specific BLDC motor. The simulation is done on MATLAB/SIMULINK environment to verify the control characteristics of the Fuzzy PID controller.**

Keywords— Brushless DC motor(BLDCM); PID controller; Fuzzy PID controller; MATLAB/Simulink.

I. INTRODUCTION

BLDCM are more compatible for digital controllers. Due to advancement of digital systems, it is very convenient to control the characteristics, which can be used in robotic, aerospace and other precise application [1]. Conventionally various speed control methods are applied to BLDCM such as PID control[2]. The characteristics of the BLDCM are non linear in nature. A non linear control system like Fuzzy logic controllers [3] are used to get better speed control characteristics. BLDCM was a multivariable and strong coupling nonlinear systems, though the advantages of traditional PID control algorithm was simple structure and good robustness, there were some shortcomings at adjusting the high precision and rapid speed of system dynamic performance and static performance[3]. A new methodology is introduced for designing and tuning the scaling gains of the conventional fuzzy logic controller (FLC) based on its well-tuned linear counterpart. The conventional FLC with a linear rule base is very similar to its linear counterpart. Fuzzy logic can be used to control a process that a human can control manually with expertise gained from experience[4]. The base is very similar to its linear counterpart. The linear three-term controller has proportional(Kp), integral(Ki) and/or derivative(Kd) gains. Similarly, the conventional fuzzy three term controller also has fuzzy proportional, integral and/or derivative gains conventional FLC with a linear rule[5]. Among them, fuzzy logic control had the good processing ability for nonlinear uncertain systems, especially suitable for the control of nonlinear large disturbance BLDC motor systems[6]. By using separate rule for PID parameter, the controlled objects achieve better dynamic steady performance[8]. The conventional PID controller is incorporated with the fixed control parameters of Kp,Ki,Kd values to inorder to control the speed within a specific range. These fixed control parameters are not ideal for vast range of Speed/Torque control application. In order to obtain the best performance of the BLDCM, these control parameters have to be dynamically adjusted with reference to the speed at which the motor is operating. This leads to the new dimension of Fuzzy logic PID controller in which the controlled parameter are dynamically updated for optimal performance of the BLDCM.

II. FUNCTIONAL ELEMENTS OF THE FUZZY PID CONTROLLER

The functional elements of the proposed Fuzzy PID controller is presented in Fig 1. The motor drive system consist of 3 phase inverter and Fuzzy logic PID controller. The control variables for PID controller(K_P,K_I,K_D) is dynamically adjusted within a specific range with reference to the speed of a motor, so as to get the optimal control characteristics. Speed estimation is done with the output from hall sensors which is built in the BLDCM.

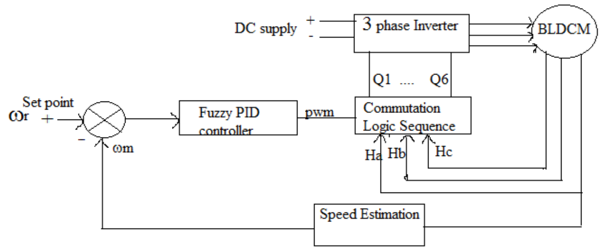

Fig. 1. Block diagram for speed control of BLDCM

Here ω_r is the set speed amd ω_m is the actual speed of the motor. The error is calculated by the difference between the above inputs. The error is given to the controller which in turn dynamically adjust the duty ratio of the PWM signal and the same is given to the commutation circuit. Based on the hall sensor inputs, and the PWM input to the commutation logic circuit the stator coils are energised for the desired speed and direction of the BLDCM.

III. MATHEMATICAL MODELING OF BLDCM

The control parameters are designed from the transfer function of the system. The mathematical modelling of the controller along with the BLDCM is discussed in the following session.

The equivalent circuit of the BLDCM is very similar to the conventional DC motor and is shown in Fig 2

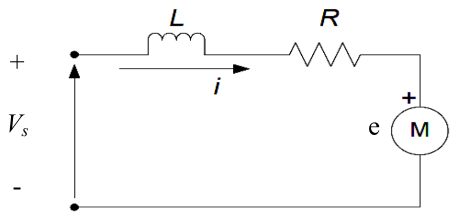

Fig. 2. Per phase Equivalent circuit of DC motor

The equivalent electro mechanical system of the BLDCM is shown in Fig 3.

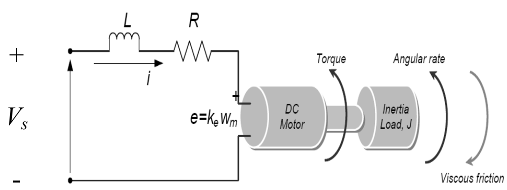

Fig. 3. Per phase Equivalent Electromechanical system of BLDCM

The basic component represented in Fig 3, are the armature resistance R , armature Inductance L and the back emf, e. Using Kirchoffs voltage law the following equations are obtained.

Using kirchoffs voltage law,

$$V_s = Ri + L\frac{di}{dt} + e \tag{1}$$

At steady state(DC state of zero frequency),

$$V_s = Ri + e \tag{2}$$

Therefore for non steady state (1)is re-arranged to make provision for the back emf,as shown in (3), Rewriting eqn (1)

$$e = -Ri - L\frac{di}{dt} + V_s \tag{3}$$

Where, $V_{s=}$ the dc source voltage

i=armature current

Considering the mechanical properties of the dc motor, from the Newtons second law of motion, the mechanical properties related to the torque of the system arrangement in the Fig 2 and 3 would be the product of the inertia load(J) and the angular velocity ($\omega_{m)}$ is equal to the sum of the all torques.

Using Newton second law,

$$J\frac{d\omega_m}{dt} = \sum T_i \tag{4}$$

$$T_e = K_f\omega_m + J\frac{d\omega_m}{dt} + T_L \tag{5}$$

Where, T_e=electrical torque

K_f=friction constant

J=inertia load

ω_m =angular velocity

$T_{L=}$ mechanical load

Electrical torque and back emf are

$$e = K_e * \omega_m \tag{6}$$

$$T_e = K_t * i \tag{7}$$

Where, K_e= back emf constant and K_t=torque constant

Rewriting (3) and (4)

$$\frac{di}{dt} = -i\frac{R}{L} - \frac{K_e}{L}\omega_m + \frac{1}{L}V_s \tag{8}$$

$$\frac{d\omega_m}{dt} = -i\frac{K_t}{J} - \frac{K_f}{J}\omega_m + \frac{1}{J}T_L \tag{9}$$

Taking laplace transform on (8)&(9)

$$si = -i\frac{R}{L} - \frac{K_e}{L}\omega_m + \frac{1}{L}V_s \tag{10}$$

$$s\omega_m = i\frac{K_t}{J} - \frac{K_f}{J}\omega_m + \frac{1}{J}T_L \tag{11}$$

For simplicity at no load(TL=0) , eqn (11)becomes,

$$i = \frac{s\omega_m + \frac{K_f}{J}\omega_m}{\frac{K_t}{J}} \tag{12}$$

Sub (12) value in (10)

$$\{(\frac{s^2J}{K_t} + \frac{sK_f}{K_t} + \frac{sRJ}{K_tL} + \frac{K_fR}{K_tL}) + \frac{K_e}{L}\}\omega_m = \frac{1}{L}V_s \tag{13}$$

Using the ratio of and the angular velocity ω_m to the source voltage V_s ,the transfer function is obtained as follows

$$G(s) = \frac{\omega_m}{V_s} = \frac{K_t}{s^2JL + (RJ + K_fL)s + K_fR + K_eK_t} \tag{14}$$

Considering the assumption, The friction constant is small,that is K_f tends to 0, this implies that

$RJ >> K_f L$ and

$K_e K_t >> RK_f$

the transfer function is re-written as:

$$G(s) = \frac{\omega_m}{V_s} = \frac{K_t}{s^2JL + RJs + K_eK_t} \tag{15}$$

Rewriting Egn (15),

$$\frac{R}{K_e K_t} * \frac{1}{R} \tag{16}$$

After manipulation Eqn (17) is obtained as,

$$G(s) = \frac{\frac{1}{K_e}}{\frac{RJ}{K_e K_t} \cdot \frac{L}{R} s^2 + \frac{RJ}{K_e K_t} .s + 1} \tag{17}$$

Mechanical (time constant) and Electrical (time constant)

$$\tau_m = \frac{RJ}{K_e K_t} \tag{18}$$

$$\tau_e = \frac{L}{R} \tag{19}$$

Substitute Eqn (18) &(19) in (17) and we get the transfer function as,

$$G(S) = \frac{\frac{1}{Ke}}{\tau_m \tau_e s^2 + \tau_m s + 1} \tag{20}$$

The combined Electro Mechanical model of BLDCM is shown in Fig 4.

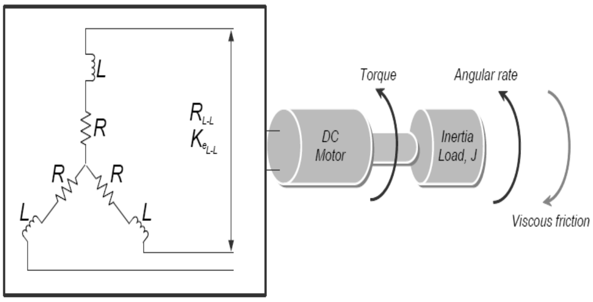

Fig 4 Electro Mechanical model of BLDCM

Mechanical time constant for the combined 3 phase system,

$$\tau_m = \sum \frac{RJ}{K_e K_t} = \frac{J \sum R}{K_e K_t} \tag{21}$$

Electrical time constant for the combined 3 phase system,

$$\tau_e = \sum \frac{L}{R} = \frac{L}{\sum R} \tag{22}$$

Eqn (21) and (22) are reframed as

$$\tau_m = \frac{J.3R}{K_e K_t} \tag{23}$$

$$\tau_e = \frac{L}{3R} \tag{24}$$

The back emf constant and torque constant

$$K_e = V.s.rad^{-1}$$

$$K_t = N.m.A^{-1}$$

The transfer function of BLDC motor is,

$$G(S) = \frac{\frac{1}{K_e}}{\tau_m \tau_e s^2 + \tau_m s + 1} \tag{25}$$

Equation 25 is the transfer function of the above system.

A. Motor Parameters

The specification of BLDCM for deriving the transfer function is given in Table I

TABLE I MOTOR PARAMETERS

BLDCM MODEL	HD92C4-64T
Maximum motor emf	380V
Maximum Speed	6000 rpm
Maximum current	12.2A
Terminal resistance phase to phase	10.4 Ω
Terminal Inductance phase to phase	43mH
Mechanical time constant	3.5ms
Torque constant	0.61 Nm/A
Rotor inertia	1.3Kg cm^2

B. Transfer Function of a HD92C4-64T BLDCM

The transfer function for the above specified BLDCM is obtained from Eqn (18),(24) and (25).

Electrical torque, τ_e

$$\tau_e = \frac{L}{3R}$$

$$= \frac{43*10^{-3}}{3*10.4}$$

$$= 137.820*10^{-5} \text{ S}$$

Back emf constant, K_e

$$K_e = \frac{3RJ}{\tau_m k_t}$$

$$=1.899 \; V.S.rad^{-1}$$

By using back emf constant and electrical time constant, the transfer function of BLDCM is given below,

$$G(S) = \frac{\frac{1}{K_e}}{\tau_m \tau_e s^2 + \tau_m s + 1}$$

$$= \frac{\frac{1}{1.899}}{\left(3.5*10^{-3}*137.82*10^{-5}\right)s^2 + \left(3.5*10^{-3}\right)s + 1}$$

$$= \frac{0.5266}{\left(4.8237*10^{-6}\right)s^2 + \left(0.0035\right)s + 1}$$

IV. CONTROLLER DESIGN

A. PID Controller

Fig 5 shows the Simulation model of the PID controller[7]. The characteristics parameters Kp,Ki,Kd gains, are applied to the system.

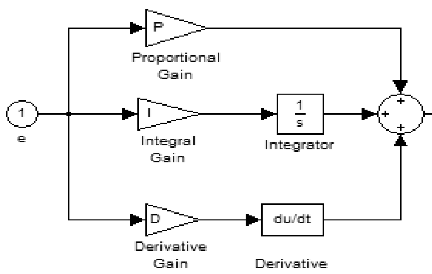

Fig. 5. Simulation model of PID controller

A PID controller is simple three-term controller. The transfer function of the most basic form of PID controller,is

$$c(s) = K_p + \frac{K_I}{S} + K_D S \tag{26}$$

$$c(s) = \frac{K_D S^2 + K_P S + K_I}{S} \tag{27}$$

Where K_p = Proportional gain, K_I = Integral gain and K_D = Derivative gain.

The output function of the controller (u) from the controller to the plant is equal to the Proportional gain (K_P) times the magnitude of the error plus the Integral gain (K_I) times the integral of the error plus the Derivative gain (K_D) times the derivative of the error.

$$u = K_p e + K_I \int edt + K_d \frac{de}{dt} \tag{28}$$

The three major parameters to be considered are

a. Rise Time: Time taken by a plant output to change from a low value to a specified high value.

b. Overshoot: In control theory, overshoot is defined as an output exceeding its final, steady state.

c. Settling Time: The time required for the response curve to reach and stay within a range of certain percentage(2% or 5%) of the final value.

By using the Ziegler Nichols method, the PID parameters are obtained and shown in Table II.

TABLE II VALUES OF PID PARAMETER

Controller	Kp	K_I	K_D
PID	2	666.67	$1.5*10^{-3}$

By using the PID parameter value, the speed control of a BLDCM is designed and the speed of a motor is maintained at a desired level.

B. Fuzzy PID controller

BLDCM is a non linear process. So non linear control of FUZZY is used. The new fuzzy-PID controller takes conventional PID as the foundation, which uses the theory of fuzzy reason and variable discourse of universe to on-line regulate the parameters of PID automatically. The structure of fuzzy PID controller is shown in Fig.6.

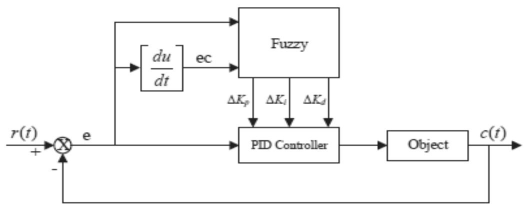

Fig. 6. Fuzzy PID controller

Here the fuzzy inputs are error (E) ,change in error (CE) and the three outputs from independent fuzzy controller K_P,K_I,K_D. The fuzzy linguistic variables are Negative Big (NB), Negative Medium(NM), Negative Small (NS), Zero (Z), Positive Small (PS),Positive Medium (PM), Positive Big (PB). Inputs are all normalized in the interval of [-3,3] and the outputs are [-1,1]. The fuzzy rules are extracted from fundamental knowledge and human experience about the process. These rules contain the input and output relationships that define the control strategy. Each control input has seven fuzzy sets so that there are at most 49 fuzzy rules. Correspondingly the rule are created for all PID parameters. Each rule uses an If – Then logic

In this Fuzzy PID controller , there are two inputs E and EC and three outputs K_P,K_I,K_D are considered The fuzzy rule for K_P ,K_I,K_D are tabulated below. With this fuzzy rule, the BLDCM Speed control using Fuzzy PID controller is simulated using MATLAB.

TABLE III FUZZY CONTROL RULES OF K_P

E/CE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

TABLE IV FUZZY CONTROL RULES OF K_I

E/CE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NB	NB	NB
NM	NM	NB	NB	NB	NB	NB	NM
NS	PM	Z	NM	NB	NB	Z	PM
Z	PB	PM	PS	NB	PS	PM	PB
PS	PM	Z	NM	NB	NM	Z	PM
PM	NM	NB	NB	NB	NB	NB	NM
PB	NB	NB	NB	NB	NB	NB	NB

TABLE V FUZZY CONTROL RULES OF K_D

E/CE	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NB	NB	NB
NM	Z	NS	NM	NM	NM	NS	Z
NS	PS	Z	Z	Z	Z	Z	PS
Z	PB	PB	PM	PS	PM	PB	PB
PS	PS	Z	Z	Z	Z	Z	PS
PM	Z	NS	NM	NS	NM	NS	Z
PB	NB	NB	NB	NB	NB	NB	NB

With this, fuzzy rule, the fuzzy PID control of a BLDCM is designed.

V. SIMULATION OF FUZZY PID CONTROLLER

Fig 7 shows the MATLAB/Simulink model for the Fuzzy PID controller to control the speed of a BLDCM.

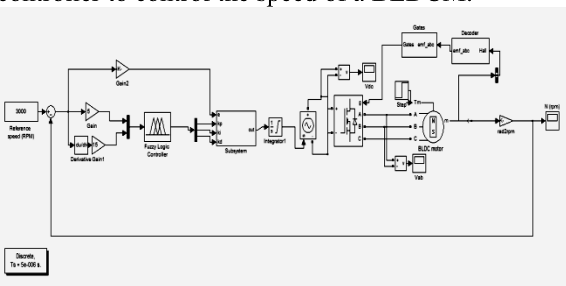

Fig. 7. Simulink model of Fuzzy PID controller

VI. SIMULATION RESULTS

Simulation is carried out for verifying the effectiveness of Fuzzy PID controller . the simulation results are compared with PID controller and found a tangible improvement in the performance characteristic. The speed response of BLDCM at 3000 rpm with PID and Fuzzy PID controller is presented in fig 8 and 9 respectively. During running condition of BLDC motor, suddenly the load of 5 N.m is applied at a time of 0.3 sec. The controller makes the speed of a motor to a desired level.

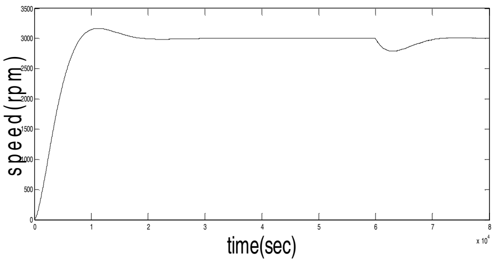

Fig .7. Response Of BLDCM Using PID Controller

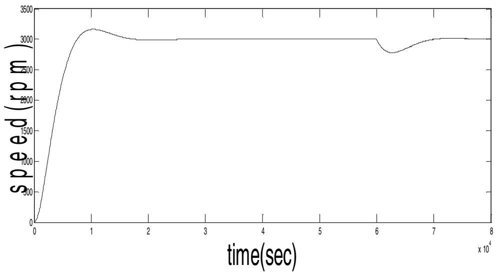

Fig. 8. Response Of BLDCM Using FuzzyPID Controller

The control characteristics of a BLDCM with PID controller and FuzzyPID controller is compared and tabulated in Table VI

TABLE VI PERFORMANCE VALUES OF THE TIME RESPONSE CURVE SHOWN IN FIG 7 , 8

CONTROLLER	RISE TIME (Sec)	SETTLING TIME (Sec)	OVER SHOOT (rpm)
PID	0.04	0.133	169
Fuzzy PID	0.039	0.119	163.5

Based on simulation observation it is found that the performance characteristics is improved while using Fuzzy PID control than the PID control.

VII. CONCLUSION

Mathematical model of BLDCM and the basic theory of the fuzzy control, double closed loop control system of fuzzy PID controller is designed, using Matlab/Simulink to build simulation model of the motor speed regulation system. By simulation result, PID control algorithm of motor, overshoot and oscillation faults, but fuzzy PID controller can react quickly, and have higher static precision. Using fuzzy PID control, it can accelerate the response speed of the motor, the control characteristic of motor has been optimized and it has profound significance for realizing high accuracy control of BLDCM.

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