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Speed Control of Brushless DC Motor: A Comparative Study

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Abstract— **In this paper a comparative study on speed control of Brushless DC Motor is presented. The mathematical model of the BLDC motor is developed and it is used to examine the performance of the controllers. Initially a PI controller is developed for the speed control of the given BLDC motor. Then the controller is upgraded to PID, and the performance of the BLDC motor is verified. Later a fuzzy logic based controller is developed for the speed control of the given BLDC motor. Unlike PI and PID controllers tuning is not required for the fuzzy logic based controllers. Through extensive simulations it is observed that the performance of fuzzy logic controller is better than all other controllers.**

I. INTRODUCTION

BRUSHLESS DC motors(BLDC) are widely used in many applications such as automotive, computer, industrial, aerospace etc. BLDC motors have several advantages over brushed DC motor. They have lower maintenance due to the elimination of the mechanical commutator and they have a high power density which makes them ideal for high torque-to weight ratio applications. Compared to induction machines, they have lower inertia allowing for faster dynamic response to reference commands. Also, they are more efficient due to the permanent magnets which results in virtually zero rotor losses.

BLDC motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal back EMF waveform shape [1]. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. In the outer speed control loop PI,PID and fuzzy logic based controllers are used and in the current control loop PI controller is used.

There are two types of permanent magnet BLDC motors, which depend on their back-EMF waveforms [2]. The BLDC motor has the trapezoidal back-EMF waveform. The one with sinusoidal back-EMF is called permanent magnet synchronous motor (PMSM). The stator winding of BLDC motor is typically trapezoidally wound in order to generate the trapezoidal shape back-EMF waveform. On the contrary, the PMSM has sinusoidally distributed winding to produce the sinusoidal type back-EMF.

Unlike the conventional controllers the current control technique used in this paper is based on a common DC signal and only one current controller is used for the three phases. Using this set up the outer control (speed control loop) loop of the BLDC drive system is controlled using PI, PID and fuzzy logic controller and performance is evaluated. The organization of the paper is as follows. The structure of permanent magnet BLDC motor is explained at section II. The mathematical model is presented in section III. Section IV gives speed control of BLDC motor. The simulation results and discussions are shown in section V and the conclusions are made in the last section.

II. PERMANENT MAGNET BLDC MOTOR

Fig. 1 illustrates the structure of a typical BLDC motor. The stator windings of BLDC are similar to those in a polyphase AC motor, and the rotor is composed of one or more permanent magnets. BLDC motors contain a powerful permanent magnet rotor and fixed stator windings. The stationary stator windings are usually three phases, which means that three separate voltages are supplied to three different set of windings [5]. BLDC motors are different from AC synchronous motors in that the former incorporates some means to detect the rotor position (or magnetic poles) to produce signals to control the electronic switches.

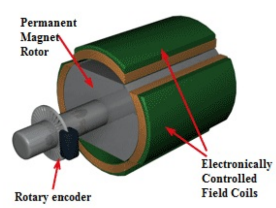

Fig. 1. Disassembled view of a BLDC motor

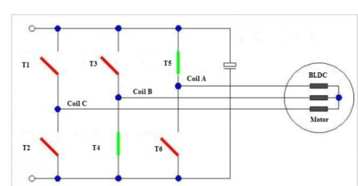

Fig. 2. Inverter fed 120^0 BLDC motor drive

Fig. 2 shows the basic diagram of conventional 120^0 BLDC motor drive. Gating signals to each inverter switching are given based on rotor position.

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III. Mathematical model of BLDC Motor

The BLDC motor has three stator windings and permanent magnets on the rotor. Since both the magnet and the stainless steel retaining sleeves have high resistivity, rotor-induced currents can be neglected and no damper windings are modeled. Hence the circuit equations of the three windings in phase variables are

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} L_a & L_{ba} & L_{ca} \\ L_{ba} & L_b & L_{cb} \\ L_{ca} & L_{cb} & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Based on the equation (1), the equivalent circuit of motors can be obtained, as shown in Fig.3.

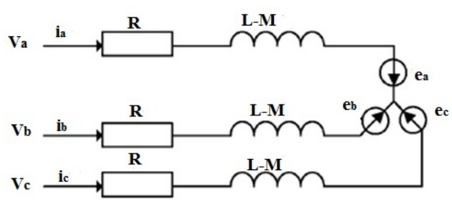

Fig. 3. The equivalent circuit of BLDC motor

It has been assumed that the stator resistance of all the windings are equal. Assuming further that there is no change in the rotor reluctances with angle, then

$$L_a = L_b = L_c = L$$
$$L_{ab} = L_{ca} = L_{cb} = M$$

Hence,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

but

$$i_a + i_b + i_c = 0 \quad (3)$$

Therefore,

$$Mi_b + Mi_c = -Mi_a \quad (4)$$

Hence

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (5)$$

and the electromagnetic torque is

$$T_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_r} \quad (6)$$

The equation of motion is

$$\rho\omega_r = \frac{(T_e - T_L - B\omega_r)}{J} \quad (7)$$

where

e_a, e_b, e_c are a, b, and c phase back-EMF's, L_a, L_b, L_c are self-inductance of a, b, and c phases, V_a, V_b, V_c are a, b, and c phase voltages, B is damping constant, J is moment of inertia and M is Mutual inductance

The trapezoidal back-EMF wave forms are modeled as a function of rotor position so that rotor position can be actively calculated according to the operation speed. The back EMF's are expressed as a function of rotor position(θ).

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = E \begin{bmatrix} f_a(\theta) \\ f_b(\theta) \\ f_c(\theta) \end{bmatrix}, (E = k_e \omega_r) \quad (8)$$

where k_e is back-EMF constant, $f_a(\theta)$, $f_b(\theta)$, and $f_c(\theta)$ are the function of rotor position.

The trapezoidal shape functions with limit values between +1 and -1:

$$f_s(\theta) = \begin{cases} (6/\pi)\theta & (0 < \theta \le \pi/6) \\ 1 & (\pi/6 < \theta \le 5\pi/6) \\ -(6/\pi)\theta + 6 & (5\pi/6 < \theta \le 7\pi/6 \\ -1 & (7\pi/6 < \theta \le 11\pi/6) \\ (6/\pi)\theta + 12 & (11\pi/6 < \theta \le 2\pi) \end{cases} \quad (9)$$

IV. Speed control of BLDC motor

Fig.4 shows the complete block diagram of three phase BLDC drive system.

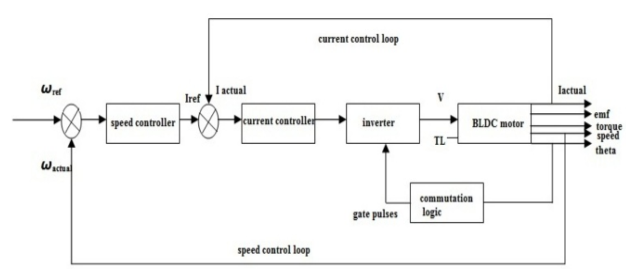

Fig. 4. BLDC motor drive system

The drive consists of speed controller, current controller, commutation logic and the voltage source inverter. Two control loops are used to control BLDC motor. The inner current control loop synchronizes the inverter gates signal with the electromotive forces.

In this paper the current control part of the BLDC drive system is implemented as follows. Fig. 5 shows the current controller block diagram. The actual current of the motor is sensed through current sensor and then rectified and a DC component with maximum current is obtained. This is then compared with its reference value and the current error is processed in PI current controller to generate PWM pulses for all the six valves of the inverter.

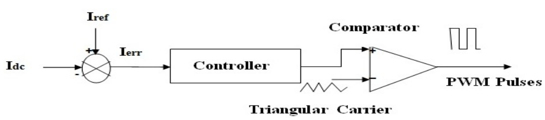

Fig. 5. Current controller block diagram

In the speed control part the speed of the motor is compared with its reference value and the speed error is processed. The output of this controller is considered as the reference torque. The PI controller is widely used in industry for speed control due to its ease in design and simple structure. But there will be overshoot, so to reduce overshoot and settling time, PID controller is used as speed controller. Later for comparison purpose a fuzzy logic controller is also used as speed controller.

A. PI Controller

Initially we tested the performance of the system using a PI controller. Fig. 6 shows the Proportional-Integral (PI) controller block diagram.

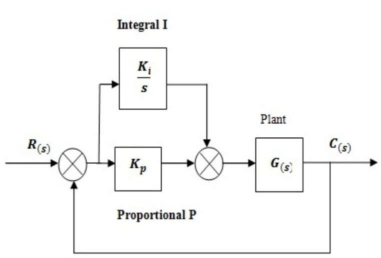

Fig. 6. PI controller block diagram

The transfer function of the most basic form of PI controller is,

$$C(s) = K_p + {K_i}/{s} \tag{11}$$

where K_p is the proportional gain and K_i is the integral gain.

If the proportional factor is too high the system will become unstable. If it is too small the system is not able to reach the set point in a given time. So the proportional factor or gain of the PI controller is tuned to maintain the speed at a desired level.

The advantage of both P-controller and I-controller are combined in PI-controller. The proportional action increases the loop gain and makes the system less sensitive to variations of system parameters. The integral action eliminates or reduces the steady state error.

B. PID Controller

In order to reduce the overshoot and settling time we then used a PID controller. Fig. 7 shows the Proportional Integral Derivative (PID) controller block diagram.

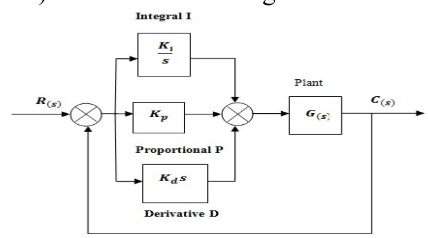

Fig. 7. PID controller block diagram

The proportional controller stabilizes the gain but produces a steady state error. The integral controller reduces the steady state error. The derivative controller reduces the rate of change of error. The combined effect of all the three cannot be judged from the parameters K_p, K_i and K_d.

The transfer function of the most basic form of PID controller is,

$$C(s) = K_p + {K_i}/{s} + K_d S \tag{12}$$

where K_p is the proportional gain, K_i is the integral gain and K_d is the derivative gain.

The proportional controller gives an output directly proportional to the error. If the error goes to zero then output of the controller is zero and the system will slow down with damping. It also causes an overshoot.

The integral controller reduces the rise time, causes an overshoot, increases the settling time and most importantly eliminates the steady state error. The important function of K_d is to reduce overshoot and reduce settling time.

C. Fuzzy Logic Controller

Later for comparison purpose we implemented a fuzzy logic controller. Fig. 8 shows the basic structure of fuzzy logic controller. Fuzzy logic's linguistic terms are most often expressed in the form of logical implications, such as If-Then rules. Fuzzy membership functions may be in the form of triangle, a trapezoid, a bell as shows in Fig. 9, or another appropriate form [9].

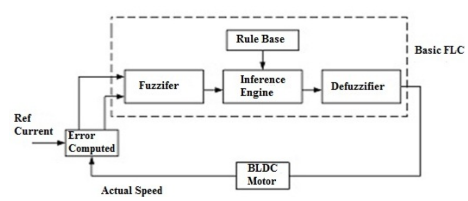

Fig. 8. Fuzzy logic controller

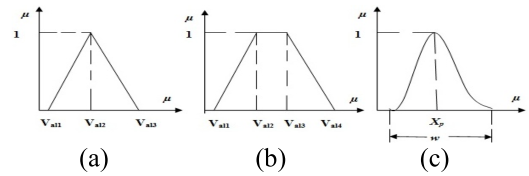

Fig. 9. (a) triangle, (b) trapezoidal, (c) bell membership function.

The inputs of the fuzzy controller are expressed in several linguistic levels shown in Fig. 10, these levels can be described as positive big (PB), positive medium (PM), positive small (PS), or in other levels. Each level is described by a fuzzy set. In general, experience and expertise are required for the implementation of fuzzification in complex systems.

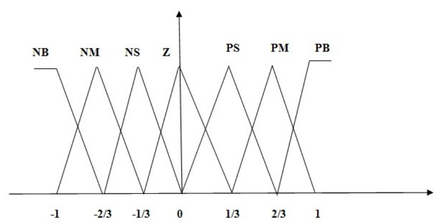

Fig. 10. Seven levels of fuzzy membership function

The rule base used for the fuzzy logic controller is given in Table I. The fuzzy inference operation is implemented by using the 49 rules. The min-max compositional rule of inference and the center of gravity method have been used in defuzzification process [10].

TABLE I. TABLE OF FUZZY RULE

E CE	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	NS
NM	PB	PM	PM	PS	PS	Z	NS
NS	PM	PM	PS	Z	Z	NS	NS
Z	PM	PS	PS	Z	NS	NS	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NS	NM	NM	NB
PB	Z	NS	NS	M	NM	B	NB

A fuzzy logic control consists of:

i. *Fuzzification:* This process converts or transforms the measured inputs called crisp values, into the fuzzy linguistic values used by the fuzzy reasoning mechanism.

ii. *Knowledge Base:* A collection of the expert control rules (knowledge) needed to achieve the control goal.

iii. *Fuzzy Reasoning Mechanism:* This process will perform fuzzy logic operations and result the control action according to the fuzzy inputs.

iv. *Deffuzification unit:* This process converts the result of fuzzy reasoning mechanism into the required crisp value.

V. RESULTS AND DISCUSSION

The simulink model in Fig. 11 is simulated using MATLAB/SIMULINK. The test machine used for simulation is a three phase BLDC motor. The machine parameters are shown in Table II. The simulink model consists of an inner current control loop and an outer speed control loop. The current control loop is implemented using PI controller. In the outer speed control loop PI, PID and Fuzzy controllers are used, the speed obtained is shown in the below figures.

TABLE II. MACHINE PARAMETER

Rated Power	0.5 hp
Rated Voltage	160V
Rated Speed	4000rpm
Rated Torque	0.89Nm
Rated Current	17.35A
No. of Poles	4

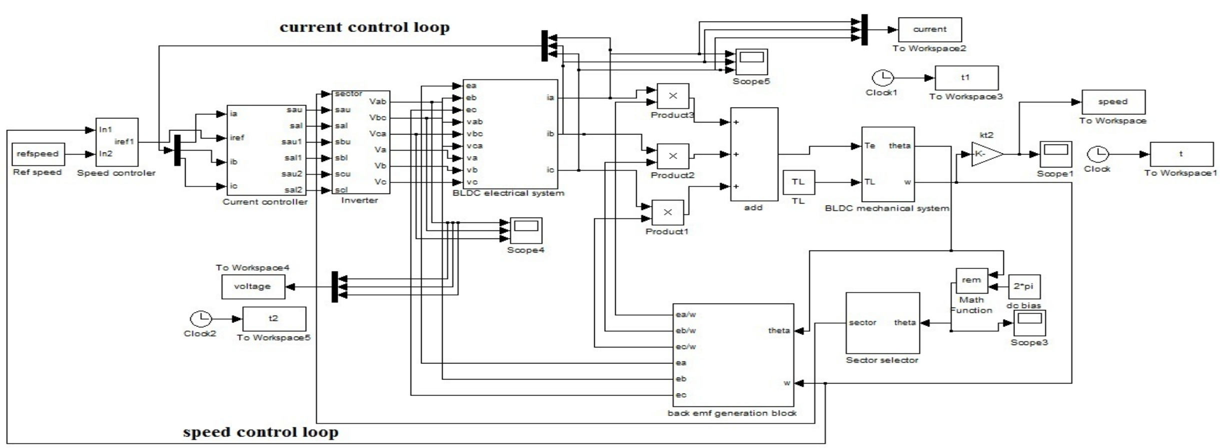

Fig. 11. Simulink Model of BLDC motor Drive

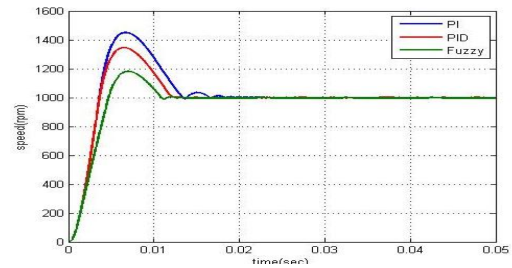

Fig.12. Speed Response of the BLDC motor with PI, PID and Fuzzy controller at 1000 rpm

Fig. 12 shows the performance of the system using PI, PID and Fuzzy controller at reference speed of 1000 rpm in loaded condition. The result shows that using PI, PID controller, the system is having a settling time of 0.0192 sec and 0.01529 sec respectively and an overshoot of 45% and 43% respectively but using a Fuzzy controller the system is having a settling time of 0.01409 sec and an overshoot of 38%.

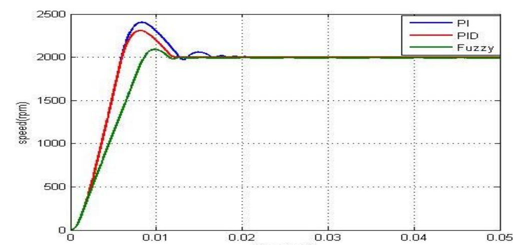

Fig.13. Speed Response of the BLDC motor with PI, PID and Fuzzy controller at 2000 rpm

Fig. 13 shows the performance of the system using PI, PID and Fuzzy controller at reference speed of 2000 rpm in loaded condition. The result shows that using PI, PID controller, the system is having a settling time of 0.01967 sec and 0.01548 sec respectively and an overshoot of 20.15% and 19.2% respectively but using a Fuzzy controller the system is having a settling time of 0.01406 sec and an overshoot of 17.05%. From the above result it is shown that a fuzzy logic controller has better performance.

Performance comparison of PI, PID and Fuzzy controllers at different speeds under loaded conditions is shown in below Table III.

Fuzzy logic controller is more efficient from other controllers such as PI and PID controller. The PI controller has some disadvantages such as high starting overshoot, sensitivity to controller gains K_i and K_p and sluggish response due to sudden change in load. The PID algorithm is simple, stable, easy adjustment and high reliability. But, in fact, most industrial process with different degrees of nonlinear, parameter variability and uncertainty of mathematical model of the system tuning PID control parameters is very difficult, poor robustness, therefore, it's difficult to achieve the optimal state under field conditions in the actual production.

When a PI controller is used in the outer speed loop, it reaches steady state time quickly. But there is overshoot in the response, so in order to reduce that a PID controller is used. This controller reduces overshoot as well as setting time. When a fuzzy logic controller is used the overshoot and settling time are reduced further.

TABLE III PERFORMANCE COMPARISON

Speed (rpm)	PI Controller		PID Controller		Fuzzy Controller	
	% Mp	t_s (ms)	% Mp	t_s (ms)	% Mp	t_s (ms)
1000	45	19.2	43	15.29	38	14.09
2000	20.15	19.67	19.2	15.48	17.05	14.06
3000	6.07	19.76	5.60	15.72	4.77	14.1
4000	1.93	20.58	1.63	17.38	0.77	15

From performance comparison fuzzy logic controller has better control performance than PI and PID controllers.

VI. CONCLUSION

The performance of a three phase BLDC drive system using PI, PID and fuzzy logic speed controllers are evaluated. It is shown through extensive simulations that the performance of fuzzy logic controller is better than PI and PID controllers. As a future scope the fuzzy logic can be combined with PID control and the performance can be evaluated.

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