Dynamic Behavior of Brushless DC Motor under the Application of PI, PD, PID, and Fuzzy Logic Controllers

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ABSTRACT

The importance of Brushless Direct Current (BLDC) motors in modern day technology cannot be overemphasized. Its improved performance in terms of efficiency, reliability, noise and dynamic response, better speed versus torque characteristics, higher speed range, and durability over the Brushed Direct Current motors could not be wished away.

This work investigates the performance of a BLDC motor with the application of PI controller, PD controller, PID controller, and fuzzy logic controller (FLC). Of paramount importance under the BLDC performance analysis are the rise time, the stability time, and sensitivity to error. Results from these analysis reveal that fuzzy logic controlled BLDC has a global performance acceptability over other considered controllers such as; Proportional Integral (PI), Proportional Derivative (PD), and Proportional plus Integral plus Derivative (PID). This work is modeled and simulated using Matlab/Simulink software.

(Keywords: PI controller, PD controller, PID controller, fuzzy logic controller, brushless DC motor, BLDC)

INTRODUCTION

The BLDC motor is widely used in applications including appliances, automotive, aerospace, consumer, medical, automated industrial equipment and instrumentation. The BLDC motor is electrically commutated by power switches instead of brushes.

Generally, motors convert electrical energy into mechanical energy using electromagnetic principles. The energy conversion method is fundamentally the same in all electric motors. Brushless DC motor needs position information for torque producing and this information is obtained by using hall sensors. To analyze the behavior of a BLDC motor, there is a need for parameters estimation (Mubeen, 2008). This is essential to fulfill the desired performance specifications of the system.

Due to wide attention the brushless DC motors are receiving especially for industrial applications because of their high torque density, high efficiency and small size, there is a need to have an insight into the characteristics of brushless DC motor in order to develop efficient methods to control the speed of BLDC motor and perform an effective model analysis. This is beneficial since the motor needs automatic control of their main parameters such as speed, position, acceleration and so on.

This is the focus of the remaining part of this work as sectioned under literature review, methodology, simulation and results discussion, and conclusion.

LITERATURE REVIEW

Amit and Mitra (2015) carried out a comparative study on the performance analysis of a BLDC motor in which a mathematical model of the BLDC motor was developed and used to examine the performance of the selected controllers. At first, a PI controller was developed for the speed control of the given BLDC motor. Then a fuzzy logic based controller was applied to the same brushless motor and their performances compared. Results derived showed that the performance of fuzzy logic controller was slightly better than PI controller.

Shivraj and Archana (2014) also carried out an analysis of a brushless dc motor by simulating 1200 mode of operations and resultant trapezoidal back EMF waveforms. The result obtained via Matlab software was acceptable and this gives important information for designing Brushless DC motor drive system.

Model-Based Design technique of Brushless DC Motor using MATLAB/Simulink with Arduino support block set was carried out by Hat *et al* (2015). The model of BLDC motor was developed using black-box modeling approach; simulations were performed based on real-time data and processed using MATLAB System Identification tool box. The PID Controller was then designed and tuned within the simulations to attain the drive performance. For real-time application, the controller code is created and uploaded into Arduino Mega embedded controller. The results obtained from simulation and experiment is conferred and compared that shows better performance of BLDC.

Venkateswarlu and Chengaiah (2013) made an attempt to simulate a speed control of separately excited DC motor with PID and fuzzy controllers. The aim of their paper was to provide an efficient method to control speed of DC motor using analog controller. Their work was able to show that fuzzy controller performs better if well modeled applied.

Vishal *et al.* (2014) were able to show that the application of Adaptive Neuro-Fuzzy Inference System to speed control of Brushless DC motor. Performance improvement was also obtained over conventional controller (PI &PID).

Siong*et al.* (2011) presented fuzzy logic controller for BLDC permanent magnet drives. The result shows that the fuzzy logic controller system provided good dynamic performances in both simulation and experimentation.

Sudhanshu*et al*. (2015) presents the applications, various control schemes used and modeling of BLDC Motor in MATLAB/SIMULINK environment.
The popularity of BLDC was also investigated by Pallavi and Ankit (2016). They considered basic operation of BLDC Motor, different control techniques and its comparison to other motors. There is a significant rise in popularity of BLDC motors in motion control applications. There are several techniques to control BLDC Motor like PI controller, PID controller, Fuzzy logic, Genetic algorithms, Neural Network, PWM Control and Sensorless Control and so on.

In addition, Parhizkar*et et al.* (2011) have presented direct torque control of BLDC motor drives with reduced starting current using fuzzy logic controller. Direct torque control proposes some advantages such as simple algorithm, simplicity to implement, faster torque response, reduced torque ripple and less sensitivity to parameters variations. Fuzzy logic controller (FLC) is used in order to eliminate overshoot that exists in speed and torque responses. In addition, by using FLC, starting current decreased due to consistency of this controller.

Oshin and Girisha (2016) presented a controller developed based on co-simulation of MULTISIM and LABVIEW for low cost brushless dc motor drive with low-resolution hall sensors. The driver circuit is built using a low cost MOSFET gate driver IC in MULTISIM and the controller is developed in LABVIEW. The effectiveness of the design was tested through the co-simulation.

Rajesh and Balaji (2014) offer a capable simulation model of PID controlled brushless dc motor drive using MATLAB / SIMULINK. The BLDC motor was efficiently controlled by PID controller. The dynamic characteristics of BLDC motor (speed and torque) as well as current and voltages of the inverter components were easily observed and analyzed by using the developed model.

Neethu*et et al.* (2016) designed several circuits for sensor-less control technique to be used in state space application and carried out its simulation in MATLAB using FLC. The sensor-less rotor position technique detects the zero crossing points of trapezoidal Back-EMF induced in the BLDC motor windings.

Sheeba and Nivedhitha (2014) presented an efficient speed control mechanism for drives using meaningful fuzzy sets and rules. The FLC was developed using a MATLAB/Simulink tool. The paper proposes the possibility of designing a control strategy, to achieve accurate speed control with the advantages of low cost. The suggested method is simple and efficient compared with the conventional controllers.

Adewuyi (2013) presented a paper whereby the performance of a selected dc motor controlled by a PID controller was investigated. Also, a fuzzy logic controller was applied to the dc motor and the performance investigated. With the application of proper expert rules, the response gives no overshoot and the settling time is of the desired value.

Ritu, *et al.* (2014) carried out a comparative study of Proportional Derivative controller, conventional PID controller and FLC for flowing fluids. In this paper, performance analysis of proportional derivative, conventional PID controller and fuzzy logic controller was carried out using MATLAB/SIMULINK applications.

METHODOLOGY

The system equation is given as follows:

The motor torque, T, is related to the armature current, i, by a constant factor K:

$$T = Ki \ . \qquad (1)$$

The back electromotive force (EMF), V_b, is related to the angular velocity by:

$$V_b = K\omega = K\frac{d\theta}{dt} \ . \qquad (2)$$

From Figure 1 the following equations based on the Newton's Law combined with the Kirchhoff's Law can be derived:

$$J\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt} = Ki, \qquad (3)$$

$$L\frac{di}{dt} + Ri = -K\frac{d\theta}{dt} \ . \qquad (4)$$

The Transfer Function is given by using the Laplace Transform, Equations **(3)** and **(4)** can be written as:

$$Js^2\theta(s) + bs\theta(s) = KI(s), \qquad (5)$$

$$LsI(s) + RI(s) = V(s) - Ks\theta(s), \qquad (6)$$

where s denotes the Laplace operator. From **(6)** we can express $I(s)$**:**

$$I(s) = \frac{V(s) - Ks\theta(s)}{R + Ls} \qquad (7)$$

Substituting **(7)** in **(5)** to obtain**:**

$$Js^2\theta(s) + bs\theta(s) = K\frac{V(s) - Ks\theta(s)}{R + Ls} \qquad (8)$$

From Equation **(8)**, the transfer function from the input voltage, $V(s)$, to the output angle, θ, directly follows:

$$\frac{\theta(s)}{V(s)} = \frac{K}{s[(R + Ls)(Js + b) + K^2]} \qquad (9)$$

The transfer function from the input voltage, $V(s)$, to the Angular velocity, ω is:

$$\frac{\omega(s)}{V(s)} = \frac{K}{(R + Ls)(Js + b) + K^2} \qquad (10)$$

The rules for fuzzy operations are presented in Table 1.

Table 1: Rule Table for Fuzzy Operations.

Change in error (de)	Error(e)				
	NEB	NEM	ZER	POM	POB
NEB	NEB	NEB	NEM	NEM	ZER
NEM	NEB	NEM	NEM	ZER	POM
ZER	NEM	NEM	ZER	POM	POM
POM	NEM	ZER	POM	POM	POB
POB	ZER	PEM	POM	POB	POB

where NEB = 0, NEM = 0.25, ZER = 0.5, POM = 0.75, and POB =1.

SIMULATION

The simulation of PI, PD, PID, and Fuzzy Logic Controllers as applied to the system was carried out using Matlab/Simulink platform as indicated in Figure 1.

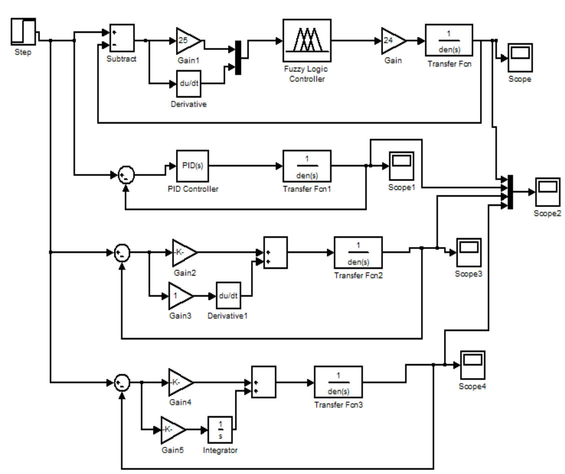

Figure 1: Matlab/Simulink Simulation Diagram.

RESULTS DISCUSSION

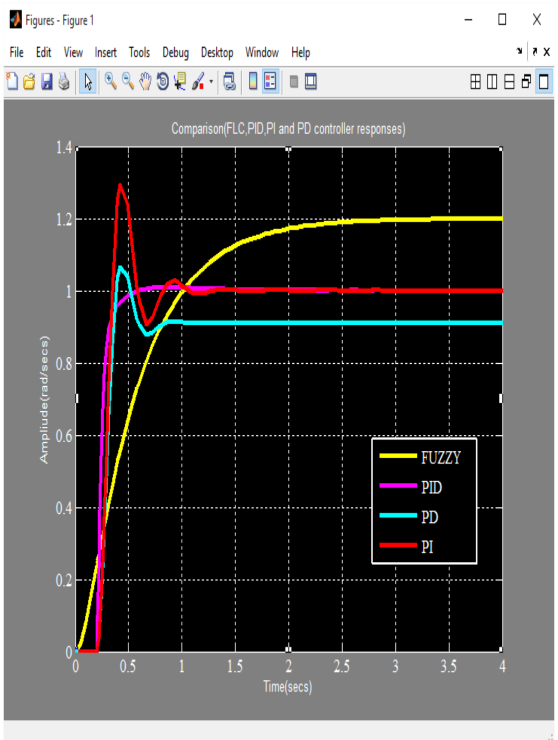

Figure 2: Comparison of Fuzzy, PID, PD, and PI Controller BLDC Motor Responses.

The motor responses above have their own distinctive specifications (time domain characteristics). These specifications describe the stability of the response derived from the various controllers. The PI, PD, and PID controller parameters address the issue of instability by affecting the system dynamics for favorable conditions depending on tuning ratio as contained in Table 2.

Table 2: The Effects of Increasing Each of the Controller Parameters K_p, K_i, and K_d.

Parameters	Rise Time	Overshoot	Settling Time
K_p(Proportional Gain)	Decrease	Increase	Small change
K_i(Integral Gain)	Decrease	Increase	Increase
K_d(Derivative Gain)	Small change	Decrease	Decrease

For Fuzzy Logic Controller the systems dynamics is affected based on the rule base which was derived using expert experience. The BLDC motor specifications for the motor response with PI, PD, PID, and Fuzzy Logic Controller are presented in Table 3.

Table 3: Output Table.

Specifications	PI controller	PD controller	PID controller	FLC
Rise time(s)	0.0998	0.105	0.132	1.07
Settling time(s)	0.774	0.547	0.257	1.95
Peak time(s)	0.24	0.23	0.59	4
Overshoot(%)	30.5	18.8	1.03	nil

All these show a great change in the performance of the BLDC motor. It is evident that the response derived from the PD controller is more stable than the PI controller since it has a lower value for its overshoot and settling time, although the response from the PI controller is faster. The PID controller response shows better performance characteristics since it possesses even smaller overshoot (which is quite close to having no overshoot), this indicates that the response is more stable compared to the response derived from the PI and PD controllers. The lower settling time value buttresses the fact that the PID response is better off than the PI and PD response in terms of stability. Comparing the PID controller and the FLC, the Fuzzy Logic controller has no overshoot although it has a settling time of 1.95secs it requires no tuning as the control is based on expert knowledge used to derive the rule base. Therefore there is really no need for human interference or manipulations.

CONCLUSION

The PD controller produces better response than the PI controller under different gain value. The PID controller produces better response than both the PI and PID controller even with different gain values. The Fuzzy Logic Controller produces the desired autonomous decision making operations unlike the PI, PD and PID controllers although sometimes the PID controller can have certain characteristics that are more desirable than those of the FLC but due to the fact that the PID controller still requires human monitoring to achieve that, the Fuzzy Logic Controller is more desirable since it could function based on the Fuzzy Inference System (FIS) designed for its operation.

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