Speed Control of Brushless DC Motor Using Fuzzy Based Controllers

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Abstract - Brushless DC Motor (BLDCM) has been widely used in industries because of its properties such as high efficiency, reliability, high starting torque, less electrical noise and high weight to torque ratio. In order to control the speed of BLDCM, a number of controllers are used. In this paper, transient performances of BLDCM with conventional controller like PID have been evaluated and the results have been compared with fuzzy based controllers. Compared to PID controller, fuzzy controllers provide better speed response but conventional controllers offer better response with changing load at the cost of long settling time. MATLAB/SIMULINK environment is used to carry out the above investigation.

Key Words: BLDC Motor, Dynamic Modeling, PID Controller, Fuzzy Logic, Speed Control etc…

1. INTRODUCTION

There are mainly two types of dc motors used in industry. The first one is the conventional dc motor where the flux is produced by the current through the field coil of the stationary pole structure. The second type is the brushless dc motor where the permanent magnet provides the necessary air gap flux instead of the wire-wound field poles. BLDC motor is conventionally defined as a permanent magnet synchronous motor with a trapezoidal Back EMF waveform shape. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. Recently, high performance BLDC motor drives are widely used for variable speed drive systems of the industrial applications and electric vehicles.

BLDC motors are rapidly becoming popular in industries such as Electrical appliances, HV AC industry, medical, electric traction, automotive, aircrafts, military equipment, hard disk drive, industrial automation equipment and instrumentation because of their high efficiency, high power factor, silent operation, compact, reliability and low maintenance. The rotation of the BLDC motor is based on the feedback of rotor position which is obtained from the hall sensors [1].To replace the function of commutators and brushes, the BLDC motor requires an inverter and a position.

Industrial drives require acute speed control and hence closed loop system with current and speed controllers coupled with sensors are required. Thus this paper presents a detailed comparison of BLDC motor with PID controller and fuzzy logic controller. The various performance parameters of the motor are observed under no load and loaded condition. The results of these were tabulated and analyzed for both the controllers. Finally the performance comparison between the PID controller and fuzzy logic controller is done. The graph is plotted with the speed response obtained from PID and fuzzy logic controller along with a reference speed of 2000rpm.

The reason why conventional controller has low efficiency such as PID controller because the overshoot is too high from the set point and it may takes delay time to get constant and sluggish response due to sudden change in load torque and the sensitivity to controller gains Ki and Kp and Kd. This has resulted in the increased demand of modern nonlinear control structures like Fuzzy logic controller which was presented by Zadeh in 1965. Besides that, fuzzy logic controller is more efficient from the other controller such as PI controller. These controllers are inherently robust to load disturbances.

BLDC motors being non-linear in nature can easily be affected by the parameter variations and load disturbances [2]. Hence the proper choice of controller is gives a better performance by reducing the problem of overshoot, settling time, and fast response. Thus in this paper the various parameters such as time of settling, peak overshoot, mean square error and steady state error were observed in simulation and a comparative tabulation is presented. The organization of the paper is as follows. Section 2 deals with the construction, working principle and operation. Section 3 deals with the modeling aspects of the motor and the details of speed controllers were included in Section 4 followed by results and simulation details in Section 5.

2. PRINCIPLE OF BLDC MOTOR OPERATION

BLDC motor consists of the permanent magnet rotor and a wound stator. The brushless motors are

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controlled using a three phase inverter. The motor requires a rotor position sensor for starting and for

providing proper commutation sequence to turn on the power devices in the inverter bridge. Based on the rotor position, the power devices are commutated sequentially every 60 degrees. The electronic commutation eliminates the problems associated with the brush and the commutator arrangement, namely sparking and wearing out of the commutator brush arrangement, thereby, making a BLDC motor more rugged compared to a dc motor. The brush less dc motor consist of four main parts Power converter, permanent magnet brushless DC Motor (BLDCM), sensors and control algorithm. The power converter transforms power from the source to the BLDCM which in turn converts electrical energy to mechanical energy. The circuit configuration of three phase inverter fed BLDC motor is shown in Fig.1.

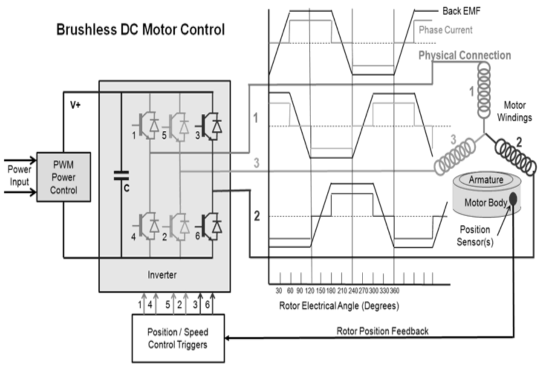

Fig -1: Sensor Based BLDC Motor Drive

One of the salient features of the brush less dc motor is the rotor position sensors, based on the rotor position and command signals which may be a torque command, voltage command, speed command and so on; the control algorithms determine the gate signal to each semiconductor in the power electronic converter. The structure of the control algorithms determines the type of the brush less dc motor of which there are two main classes voltage source based drives and current source based drives. The back emf waveform of the motor is indicated in the Fig. 2.

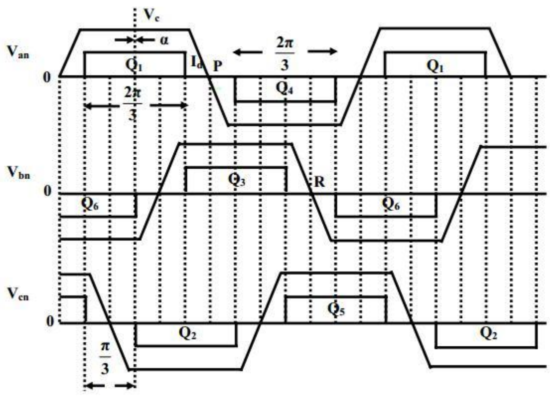

Fig -2: Back emf waveform obtained for BLDC motor

However, machine with a non sinusoidal back emf results in reduction in the inverter size and reduces losses for the same power level [1-2].

3. DYNAMIC MODELING OF BLDC MOTOR

BLDC motor can be modeled in the 3-phase ABC variables which consist of two parts. One is an electrical part which calculates electromagnetic torque and current of the motor. The other is a mechanical part, which generates revolution of the motor. Fig 3 shows the mathematical model of BLDC motor.

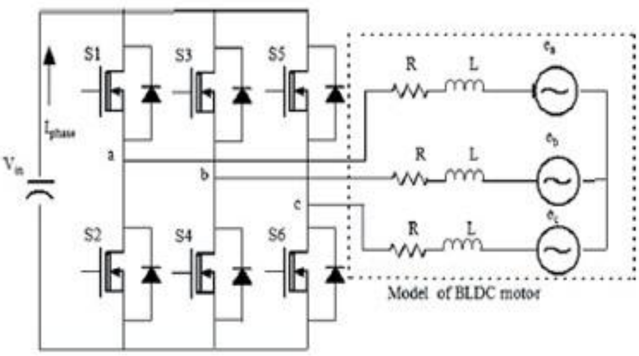

Fig. 3: Mathematical model of BLDC motor

Using KVL the voltage equation from Fig. 3 can be expressed as follows:

$$V_a = R * i_a + L * \frac{di_a}{dt} + M * \frac{di_b}{dt} + M * \frac{di_c}{dt} + e_a \quad (1)$$

$$V_b = R * i_b + L * \frac{di_b}{dt} + M * \frac{di_b}{dt} + M * \frac{di_a}{dt} + e_a \quad (2)$$

$$V_c = R * i_c + L * \frac{di_c}{dt} + M * \frac{di_b}{dt} + M * \frac{di_a}{dt} + e_c \quad (3)$$

Where,

L represents per phase armature self-inductance [H], R represents per phase armature resistance [Ω],

Va , Vb, and Vc indicates per phase terminal voltage [V],

ia , ib and ic represents the motor input current [A],

ea, eb and ec indicates the motor back-EMF developed [V].

M represents the armature mutual-inductance [H].

In case of three phase BLDC motor, we can represent the back emf as a function of rotor position and it is clear that back-EMF of each phase has 120^0 shift in phase angle.

Hence the equation for each phase of back emf can be written as:

$$e_a = K_w f(\theta_e)\ \omega \quad (4)$$

$$e_b = K_w f(\theta_e - 2\Pi/3)\ \omega \quad (5)$$

$$e_c = K_w f(\theta_e + 2\Pi/3)\ \omega \quad (6)$$

where,
K_w denotes per phase back EMF constant [V/rad.s-1],
θ_e represents electrical rotor angle [rad],
ω represents rotor speed [rad.s-1].

The expression for electrical rotor angle cab be represented by multiplying the mechanical rotor angle with the number of pole pair's P:

$$\theta_e = \frac{p}{2} * \theta_m \quad (7)$$

where,
θ_m denotes mechanical rotor angle[rad]

The summation of torque produced in each phase gives the total torque produced, and that is given by:

$$T_e = \frac{(ea*ia + eb*ib + ec*ic)}{\omega} \quad (8)$$

Where,
Te denotes total torque output [Nm].

Mechanical part of BLDC motor is represented as follows:

$$T_e - T_l = J * \frac{d\omega}{dt} + B*\omega \quad (9)$$

Where,
T_l denotes load torque [Nm],
J denotes of rotor and coupled shaft [kgm^2], and
B represents the Friction constant [$Nms.rad^{-1}$].

4. SPEED CONTROLLERS

Many drive systems today employ a conventional controller such as a PID-type controller. This method works well, but only under a specific set of known system parameters and load conditions. However, deviations of the system parameters or load conditions from the known values cause the performance of the closed-loop system to deteriorate, resulting in larger overshoot, larger rise time, longer settling times and, possibly, an unstable system. It should be noted that the system parameters such as the system inertia and damping ratio might vary over a wide range due to changes in load conditions. Generally, a PID speed controller could be tuned to a certain degree in order to obtain a desired performance under a specific set of operating conditions. Less than ideal performance is then observed when these operating conditions vary. Thus, there is a need for other types of controllers, which can account for nonlinearities and are somewhat adaptable to varying conditions in real time. Other methods are now being employed, such as fuzzy logic, in order to achieve a desired performance level.

4.1 PID Controller

A controller that combines concept of Proportional, Integral and Derivative terms by taking the sum of product of error multiplied by corresponding gains[4-5]. The output of PID controller can be mathematically represented as below.

$$C(s) = (Kp + \frac{(Ki)}{s} + s*K_d)*e(t) \quad (10)$$

Where
K_p denotes the proportional gain,
K_i denotes the integral gain and
K_d denotes the derivative gain

4.1 Fuzzy Controller

Fuzzy logic control (FLC) is a rule based controller. It is a control algorithm based on a linguistic control strategy which tries to account the human's knowledge about how to control a system without requiring a mathematical model. The approach of the basic structure of the fuzzy logic controller system is illustrated in Fig.4.

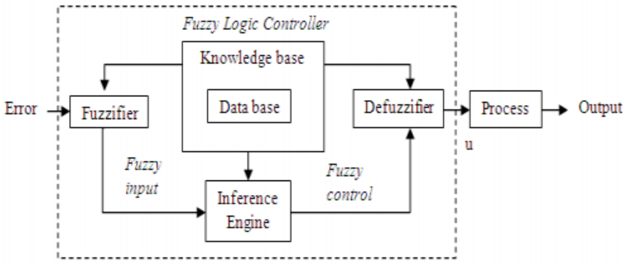

Fig. 4: Basic structure of Fuzzy logic controller

Fuzzy logic uses linguistic variables instead of numerical variables. The process of converting a numerical variable (real number or crisp variables) into a linguistic variable (fuzzy number) is called Fuzzification. Here the inputs for Fuzzy Logic controller are the speed error (E) and change in speed error (CE). Speed error is calculated with comparison between reference speed and the actual speed. The fuzzy logic controller is used to produce an adaptive control so that the motor speed can accurately track the reference speed. The reverse of Fuzzification is called Defuzzification. The use of Fuzzy Logic Controller (FLC) produces required output in a linguistic variable (fuzzy number). According to real world requirements, the linguistic variables have to be transformed to crisp output. The membership function is a graphical representation of the magnitude of participation of each input. There are different memberships functions associated with each input and output response. Here the trapezoidal membership functions are used for input and output variables. The number of membership functions determines the quality of control which can be achieved using fuzzy controller. As the number of membership function increases, the quality of control improves. As the number of linguistic variables increases, the computational time and required memory increases. Therefore, a compromise between the quality of control and computational time is needed to choose the number of linguistic variables. The most common shape of membership functions is triangular, although trapezoidal and bell curves are also used, but the shape is generally less important than the number of curves and their placement[6].

The processing stage is based on a collection of logic rules in the form of IF-THEN statements, where the IF part is called the "antecedent" and the THEN part is called the "consequent". The knowledge base comprises knowledge of the application domain and the attendant control goals. It consists of a data "base" and a linguistic (fuzzy) control rule base. The data base provides necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in an FLC. The rule base characterizes the control goals and control policy of the domain experts by means of a set of linguistic control rules. Decision making logic is the kernel of an FLC.

The most important things in fuzzy logic control system designs are the process design of membership functions for input, outputs and the process design of fuzzy if-then rule knowledge base. Fig 5 shows the membership function of speed error (E), change in speed error (CE)[7].

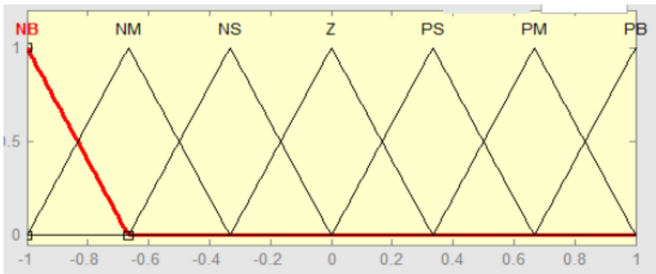

Fig -5: Membership function for error and change in error

Fig.6 shows the membership function of output variable.

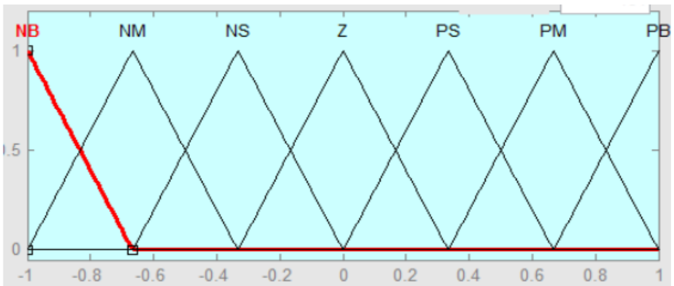

Fig -6: Membership functions for output

In practice, one or two types of membership functions are enough to solve most of the problems. The next step is to define the control rules. There are no specific methods to design the fuzzy logic rules. However, the results from PI controller give an opportunity and guidance for rule justification. Therefore after thorough series of analysis, the total 49 rules have been justified as shown in Table 1.

Table -1: Rule base for Fuzzy Controller

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

5. SIMULATION AND RESULTS

The Simulink model of BLDC motor developed based on the mathematical equations is shown in Fig.7 This Simulink model consists of an inverter block, hall signal generation block, main BLDC model block and controller block. The main BLDC model block, further consist of a current generator block; speed generator block and emf generator block. Here the performance analysis of different conventional controllers against an increase in load after duration of .2 sec has been evaluated.

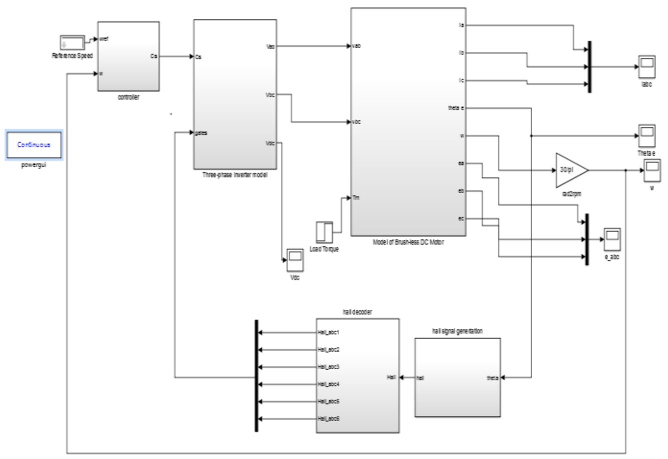

Fig.7: Simulink Model of Inverter Fed BLDC Motor

Here simulation is carried out for three cases. In case 1 BLDC with open loop control, Case 2 BLDC with Closed loop PID Control on increase in load torque and Case 3 BLDC with Closed loop Fuzzy Control on Increasing Load. The motor parameters chosen for the simulation based on the mathematical equations has been given in Table 2.

Parameters	Specification
Number of Pole Pairs, P	4
Supply Voltage. V_{dc}	12 V
Armature Resistance, R	1Ω
Self Inductance, L	20 mH
Motor Inertia, J	0.005 kgm²
EMF constant, K_e	.763 (V/rad)
Torque Constant, Kt	.345 Nm/A

Fig.8 shows the no load speed of the motor with open loop control. At no load with open loop without any controller, motor is achieving a speed of 2300 rpm.

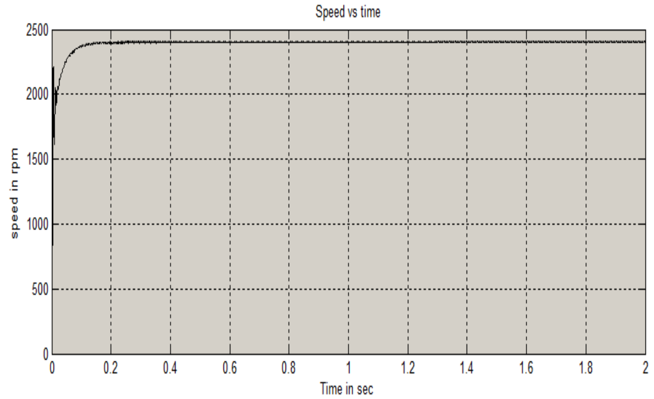

Fig.8: Open loop speed response of BLDC Drive

Fig.9 shows the trapezoidal back emf wave form. Here we have considered 120 degree mode of operation

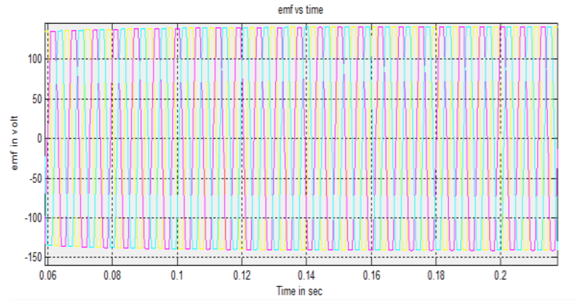

Fig.9: Back EMF of BLDC Motor

Fig.10 shows the three phase currents of motor. Earlier the value of current is high, and once the speed reaches rated value, the magnitude of current will decreases.

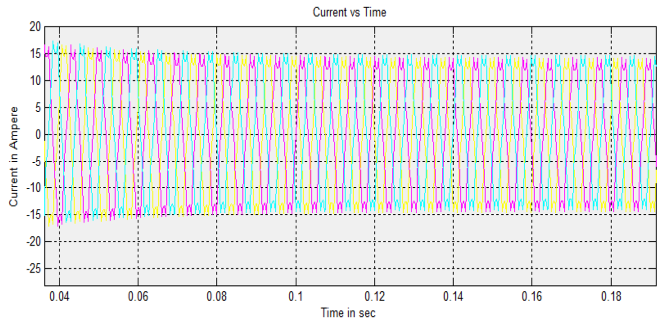

Fig.10: Current waveform of BLDC Motor

Fig.11 shows the closed loop speed response of BLDC motor with PID controller. The speed response in obtained after introducing an increase in load torque after .2 sec.

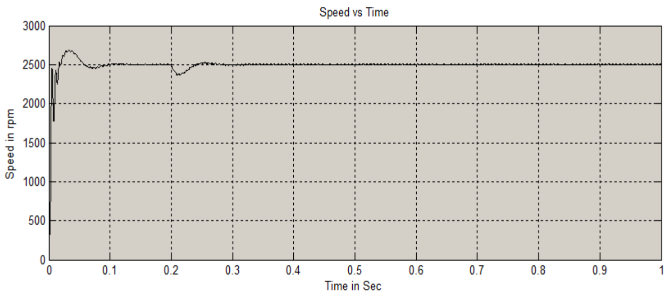

Fig.11: Closed loop control of BLDC motor with PID controller

The closed response of BLDC motor with Fuzzy controller has been shown in Fig.12.

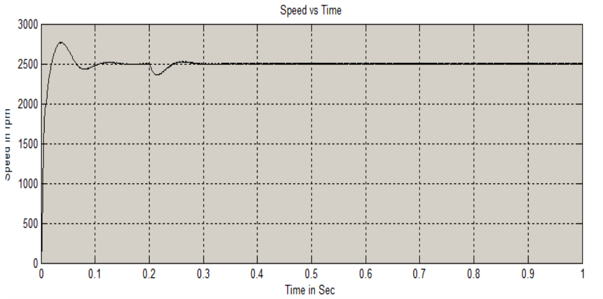

Fig.12: Closed loop control of BLDC motor with Fuzzy controller

To evaluate the performance of BLDC motor, a number of measurements are taken. The transient performance results of Conventional PID controller and Fuzzy logic controller of three phases BLDC Motor is shown in below Table 3. We consider the following characteristics Rise Time (t_t), overshoot (M_p), Settling Time (t_s), Steady state error (ess) and stability.

Parameter	PID Controller	Fuzzy Controller
Rise Time (t_r)	1.8 ms	1.1 ms
Settling Time (t_s)	1.4 sec	.9 sec
Over shoot (M_p)	8.4%	6.1%
Steady State Error (ess)	5%<	4%<
Stability	Better	Moderate

6. CONCLUSIONS

The performance of three phase BLDC motor with Fuzzy and PID controllers are analyzed. The performance of the two controllers are compared on the basis of various control system parameters such as steady state error, rise time, peak overshoot, recovery time and settling time. It is found that the control concept with fuzzy logic controller outperforms classical PID controller in most of the aspects. Simulation results of the two controllers have been presented.

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