# Speed Control of Brushless DC Motor using Fuzzy Logic & PI Controller

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*Abstract*— This paper presents the design with implementation of fuzzy logic controller to control the speed control of Brushless DC Motor. A Brushless DC Motor (BLDCM) drive is characterized by higher efficiency, lower maintenance, higher cost, silent operation & compact form. Speed control of Brushless DC Motor can be achieved by many conventional methods. This paper will show that Fuzzy logic approach will have a number of advantages over conventional methods. In order to control the speed of Brushless DC Motor, A fuzzy logic is developed which will control speed according to the operation. The PI and Fuzzy Logic control has an importance in field of control of BLDC motor. In this paper Fuzzy logic and PI Controllers are used to control the speed of BLDC Motor and their comparisons are done. Fuzzy Logic controller will work according to the magnitude of error. Simulation analysis is done of the fuzzy logic controller.

***Key words:*** Brushless DC (BLDC) motor, PI control, Fuzzy Control, Speed control

## I. Introduction

Brushless DC motors are very popular in a wide variety of applications. Compared with a DC Motor, the BLDC motor uses an electronic commutator rather than a mechanical commutator [1]. As the name implies, BLDC motors do not use brushes for commutation instead they are electronically commutated [2]. Basically BLDC motors are synchronous motor. BLDC motors do not experience slip factor. BLDC motors are in different configurations like single phase, 2-phase and 3-phase. Out of these, 3-phase motors are popular and widely used. Brushless DC (BLDC) motors have the advantage of higher power density than other motors such as induction motors because of having no copper losses on the rotor side and they do not need mechanical commutation mechanisms as compared with DC motors, which result in compact and robust structures. With these features, BLDC motors have become more popular in the applications where efficiency is a critical issue, or where spikes caused by mechanical commutations are not allowed. A BLDC motor requires an inverter and a rotor position sensor to perform commutation process because permanent magnet synchronous motor does not have brushes and commutators in DC motors [3].

Many Papers have presented different control schemes for BLDC motor. In [4] a PI controller has been used to control BLDC motor. The PI controller is only suitable for linear motor control. Most widely used controllers are conventional controllers PI and PID. PI control is a versatile & effective approach to deal with various systems [5].

In this paper, fuzzy logic control is introduced in speed regulation system of the motor. In order to improve the performance of fuzzy controller, an increase in the number of inputs & membership functions was necessary. By individual set of rules, the controller can adapt to any change of parameter. The simulation results show that performance of fuzzy logic controller has been better control performance than conventional controllers.

## II. Principle of Operation

The working of BLDC motor is similar to the conventional DC motor with the mechanical commutation replaced by an electronically controlled commutation system [6]. BLDC motors generally have the rotating permanent magnets and stationary armature. BLDC motors are used as star connected as well as delta connected motors. With the help of intelligent electronic controller, we can control power distribution. The electronic controller must have rotor position information for proper commutation of currents in the respective stator windings. Hall effect sensors are used to sense the rotor position. These sensors are embedded in the stator and thus stator windings are energized accordingly.

There are two types of BLDC motor drive control 1. Sensor mode 2. Sensor less mode. Use of sensor less control offers the advantage of reduced cost. The sensor less control offers low performance at transients or low speed range with increase in complexity of the control electronics. So we use Hall sensors for effective control of BLDC motor. A brushless dc motor consists of a permanent magnet synchronous motor that converts electrical energy to mechanical energy, a position sensor and an inverter [7]. It consists of a permanent magnet rotor with a three-phase stator winding connected in star connection. BLDC motor is driven by a three-phase inverter which is triggered from the rotor position with respect to stator reference. Hall sensor, resolver or encoder can be position sensors used to detect the rotor position and commutation is based on these sensor inputs. The cross section view of BLDC motor is shown below in fig. 1.

The power electronic driver of a BLDC motor can be an IGBT based inverter or MOSFET based inverter. The MOSFET based inverter is shown below in fig. 2.

Sensing rotor positions enables commutation logic for the three phase inverter circuits that contain MOSFET switches. Where Q1 - Q6 represents the MOSFETs in the Switching circuit and Ha, Hb, Hc represents the Hall sensor signals. The Hall sensors should be kept 120˚ apart. This is done to obtain symmetrical operation of motor phases. After sensing rotor positions, three bit codes of Hall sensed signal is obtained as shown in TABLE I. Each code specifies the rotor position and the corresponding stator windings that are to be energized. The status of Ha, Hb, Hc signals are high or low depending whether the sensor is near the N or S pole of the rotor magnets. Depending on these signals the MOSFETs switches Q1 - Q6 are ON/OFF. From TABLE I it is concluded that whenever Hb is high, the switch Q2-Q3 conducts energizing the corresponding stator windings are energized.

 

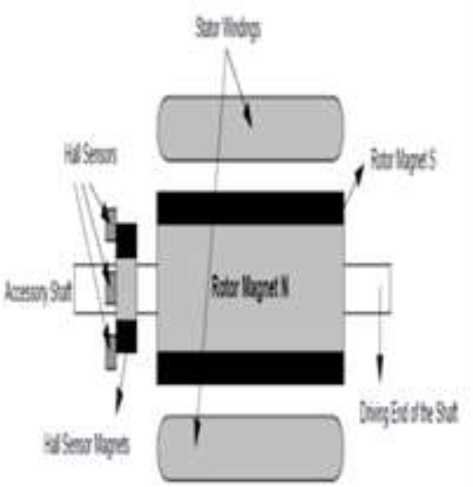


Fig. 1: Cross section view of BLDC motor

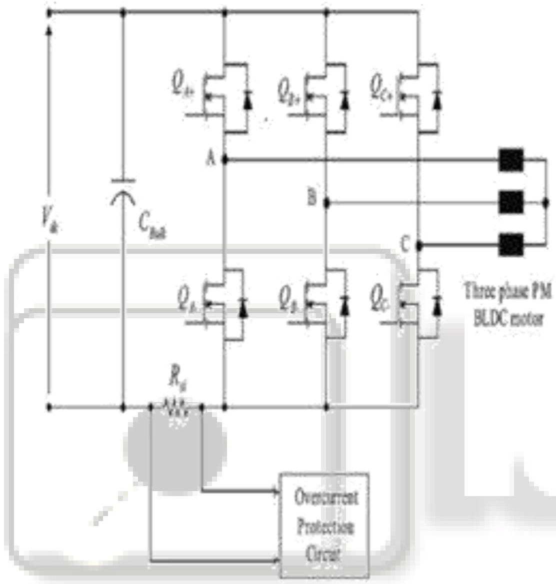


Fig. 2: Three-phase MOSFET inverter driven BLDC motor

| $H_a$ | $H_b$ | $H_c$ | $Q_1$ | $Q_2$ | $Q_3$ | $Q_4$ | $Q_5$ | $Q_6$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 |
| 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 |
| 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 1: Clockwise hall sensor signals and drive signals

## III. SPEED CONTROL SYSTEM OF BLDC MOTOR

The complete block diagram of speed control of three-phase BLDC Motor is below Fig. 3. There are two control loops. These loops are used to control the speed of BLDC motor. The inner loop does synchronization between the inverter gates signals with the electromotive forces. The outer loop controls the motor's speed by varying the DC bus voltage.

The Drive circuit consists of three phase power convertors, which use six power transistors to energize two BLDC motor phases concurrently. The rotor position determines the switching sequence of the MOSFET transistors. The rotor position is detected by means of 3 Hall sensors mounted on the stator. By using Hall sensor and the sign of reference current (produced by Reference current generator), Decoder block generates signal vector of back EMF.

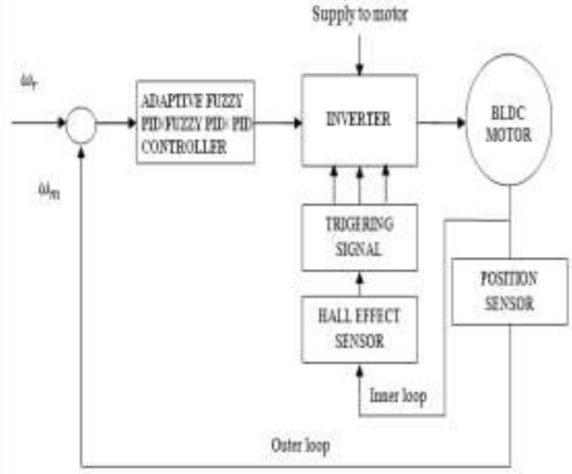


Fig. 3: Block diagram of speed control of BLDC motor

## IV. SPEED CONTROLLERS USED

There are various types of controllers used for the purpose of speed control of BLDC motor. The main function of speed controller block is to provide a reference torque. This reference torque in turn is converted to reference current and is fed to current reference generator. The output of the speed controller is limited to a proper value. This value must be according to the motor rating to generate the reference torque. The speed controllers used in BLDC motor are PI controller, PID controller, Fuzzy logic controller, Neural Network, Fuzzy PID and Genetic Algorithms.

### *A. PI Controller*

The proportional plus integral (PI) controller is widely used for industrial applications. The input to the PI controller is the speed error (E). The output of the PI controller is used as the input of reference current block. The basic structure of PI controller is shown in fig. 4.

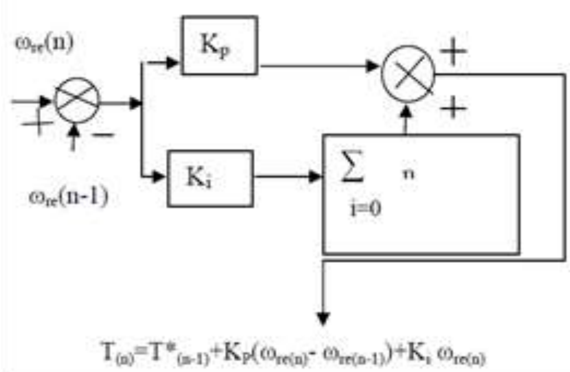


Fig. 4: Basic structure of PI controller

The model of PI speed controller is given by,

$$G(S) = Kp + Ki/s$$

Where G(S) is the controller transfer function which is torque to error ratio in s - domain, Kp is the proportional gain and Ki is the integral gain. The tuning of these parameters is done using Ziegler Nichols method using the phase and gain margin specifications. The specifications of the drive application are usually available in terms of percentage overshoot and settling time. The PI parameters are chosen so as to place the poles at appropriate locations to get the desired response. These parameters are obtained using Ziegler Nichols method which ensures stability. From the dynamic response obtained by simulation, the percentage overshoots Mp and settling time ts which are the measures of transient behavior are obtained.

The speed loop of the typical BLDC motor is shown in Figure 3 under no load condition. The closed loop transfer function of the system shown in Figure.5 is given by

$$T(s) = \frac{K_P\, s + K_I/J}{s^2 + (B + K_p)s + K_I/J}$$

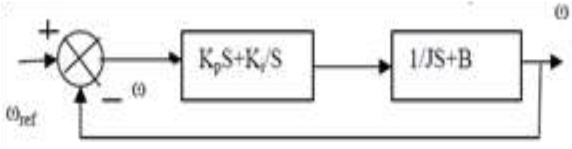


Fig. 5: Speed control using PI controller

Where T(s) is the closed loop transfer function and Kp, Ki are the PI controller parameters, J is the moment of inertia and B is the coefficient of friction. Comparing the characteristic of the transfer function with a standard 2nd order system characteristic equation we get

$$K_p = 2\xi\omega_n J\text{-}B$$
$$K_i = J\,\omega_n^2$$

1) Overshoot: how much the peak level is higher than the steady state, normalized against the steady state.
2) Settling Time: the time it takes for the system to converge to its steady state.
3) Steady-State Error: the difference between the steady-state output and the desired output.

### B. *Fuzzy Logic Controller*

The speed control of BLDC drive can be simulated using the fuzzy logic controller. The Fuzzy logic system plays a central role in the controlling of nonlinear systems and in industrial applications where the control and automation plays a vital role. The fuzzy logic control is designed using the fuzzy inference systems with the definition of input and output membership functions. The fuzzy sets and rules are designed and accordingly the drive can be controlled.

Fuzzy logic controller (FLC) is capable of improving its performance in the control of a nonlinear system whose dynamics are unknown or uncertain. Fuzzy controller is able to improve its performance without having to identify a model of the plant. Fuzzy control is similar to the classic closed-loop control approaches but differs in that it substitutes imprecise, symbolic notions for precise numeric measures.

Fuzzy controllers are more robust because they can cover a wide range of operating conditions. Fuzzy controllers are more flexible and the modifications of the Fuzzy rules are simpler when compared to the conventional controllers. With these benefits Fuzzy controllers can be utilized as industrial tool for control applications.

The fuzzy controller takes input values from the real world. These crisp input values are mapped to the linguistic values through the membership functions in the fuzzification step. A set of rules that emulates the decision making process of the human expert controlling the system is then applied using certain inference mechanisms to determine the output. Finally, the output is mapped into crisp control actions required in practical applications in the de-fuzzification step.

In a fuzzy controller the data passes through a pre-processing block, a controller, and a post-processing block. Pre-processing consists of a linear or non-linear scaling. Linguistic variables are central to fuzzy logic manipulations. They are non-precise variables that often convey a surprising amount of information. Usually, linguistic variables hold values that are uniformly distributed (μ) between 0 and 1, depending on the relevance of a context dependent linguistic term. The collection of rules is called a rules base and the rules are in the familiar if-then format, and formally the if-side is called the condition and the then-side is called the conclusion. The computer is able to execute the rules and compute a control signal depending on the measured inputs error and change in error. Therefore the rules reflect the strategy that the control signal should be a combination of the reference error and the change in error. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic.

The mapping then provides a basis from which decisions can be made. The process of fuzzy inference involves membership functions, fuzzy logic operators, and if-then rules.

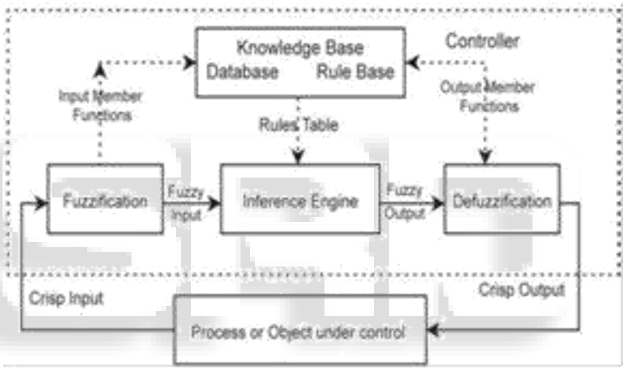


Fig. 6: Basic block diagram of FLC

The basic block diagram of the speed control of BLDC motor drive using Fuzzy logic controller is illustrated in Fig.7.The error signal generated as the result of variation in the reference speed and the actual speed of the motor sensed by the hall signals is utilized for the formulation of Fuzzy rules which results in the generation of the PWM signals to drive the switching circuit and with flexibility of fuzzy controllers wide range of speed can be controlled using this Fuzzy controller.

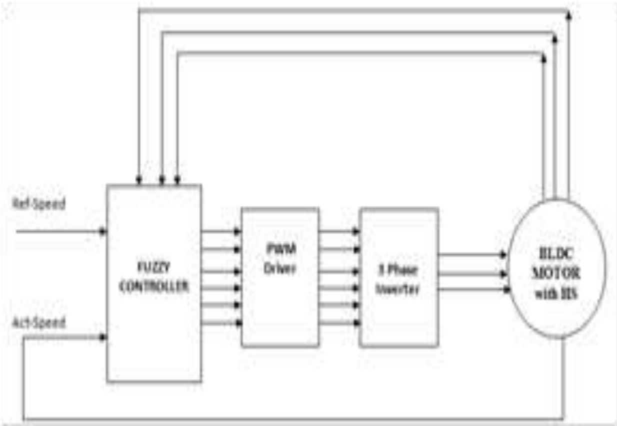


Fig. 7: Block diagram of fuzzy controlled BLDC motor drive

1) Step1: The Fuzzy rules are designed and the rules that are verified are invoked using the membership functions and the truth values obtained.
2) Step2: The result is mapped to the membership function and the variable to control the output variable.
3) Step3: The final step is the defuzzification providing the crisp output needed to control the system. The combination of fuzzy operation and rule based inference system provides a fuzzy expert system.

The membership functions illustrated in Fig.6 used to fuzzification two input values and defuzzification output of the fuzzy controller. For seven clusters in the membership functions, seven linguistic variables are defined as: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB).

It has three main components,

1) Fuzzifier
2) Inference engine.
3) Defuzzifier.

By this structure, first we convert crisp value into fuzzy value .it is called fuzzification, & last we convert fuzzy value into crisp value, called defuzzification. Between these two blocks we do decision making process, in this process we make rule base & get the accurate result.

Fuzzy logic terms are expressed in the form of logical implication. Such as if- then rules. It is called member ship function.

### C. *Defuzzification*

It converts fuzzy value into crisp value there are three methods for defuzzification,

1) The max criterion method

It produce a point at which membership function reaches maximum value.

2) The height method

The centroid of each membership function for each rule is first evaluated. The final output is then calculated as the average of the individual centroids.

3) Centroid method

It generates the center of gravity of the area by membership function.

There are seven clusters in the membership functions, with seven linguistic variables defined as: Negative Big (NB), Negative (N), Negative Small (NS), Zero (Z), Positive Small (PS), Positive (P), and Positive Big (PB). A sliding mode rule-base, used in the fuzzy logic controller is given in Table 1. 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 the “defuzzification” process.

- If p1 is NB and p2 is NB Then out is PB,
- If p1 is NB and p2 is N Then out is PB,
- If p1 is NB and p2 is NS Then out is P,
- If p1 is NB and p2 is Z Then out is P,

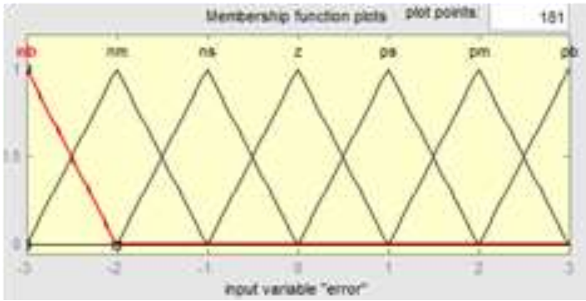


Fig. 8: Fuzzy input variable “error”

### D. *Membership Function*

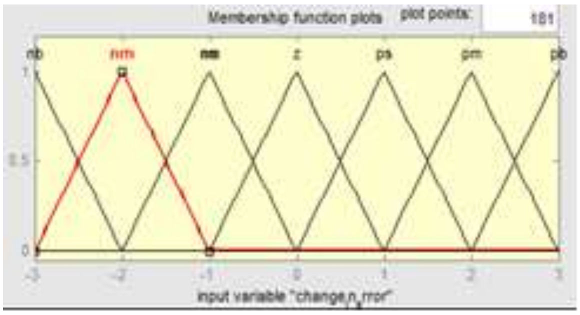


Fig. 9: Fuzzy input variable “change in error” membership function

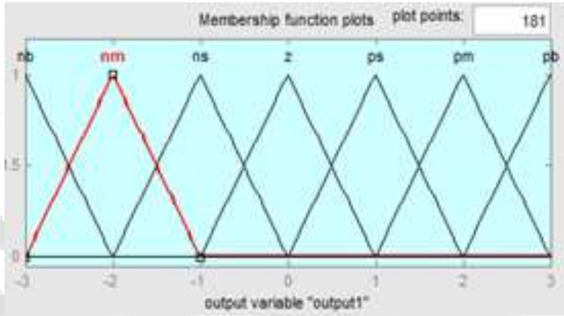


Fig. 10: Fuzzy output variable “output” membership function

| e \ C(e) | 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 | NS | Z | PS | PM | PB |
| PM | NS | Z | PS | PM | PB | PB | PB |
| PB | Z | PS | PM | PB | PB | PB | PB |

Table 2: Rule Base for Fuzzy Logic

## V. SIMULATION AND RESULTS

In this simulation, we have applied Fuzzy and PI control to control the speed in speed controller loop. Which will compare the reference speed with the actual speed and then it will generate a speed error which will be fed to the 3-phase inverter block. The actual speed of motor is compared with reference speed to control 3- phase inverter to adjust the terminal voltage.

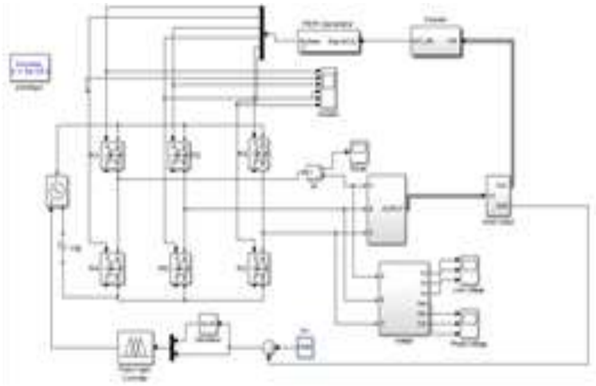

Fig. 11: Simulink model of brushless DC motor using fuzzy logic controller

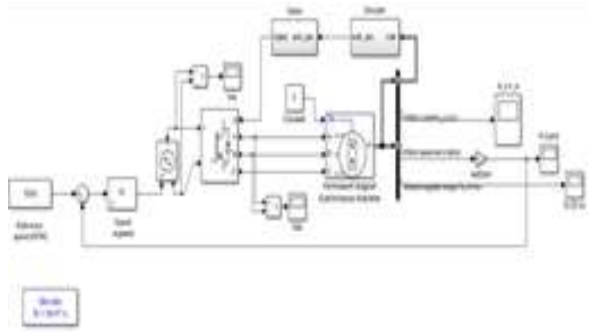

Fig. 12: Simulink model of brushless DC motor Using PI controller

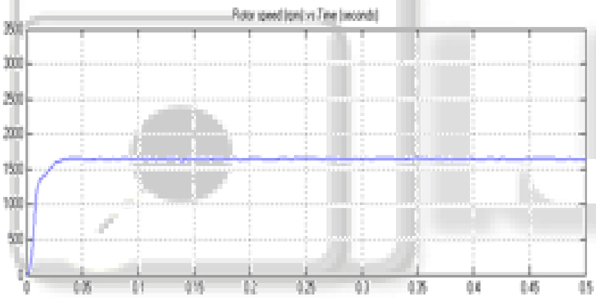

Fig. 13: Speed vs. time using fuzzy logic

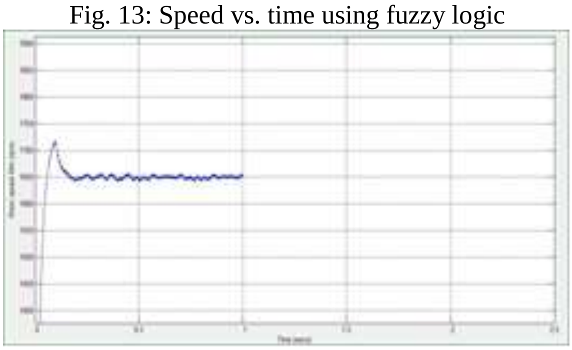

Fig. 14: Speed vs. time response using PI controller

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