SIMULATION OF SPEED CONTROL OF BRUSHLESS DC MOTOR, WITH FUZZY LOGIC CONTROLLER

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Abstract— The electronically commuted Brushless DC motors are widely used in many industrial applications which increase the need for design of efficient control strategy for these noiseless motors. This paper deals with the efficient speed control mechanisms for these drives using meaningful fuzzy sets and rules. The fuzzy logic controller is developed using a MATLAB/ Simulink tool. The paper deals with the possibility of designing a control strategy, to achieve accurate speed control with the advantages of low cost. The proposed method is simple and efficient compared with the conventional controllers.

Keywords— BLDC motor drive, Fuzzy Logic Controllers, Fuzzy sets and Fuzzy rules, Speed control.

I. INTRODUCTION

A. BLDC Motor with Hall Sensors

Brushless DC motors works similar to the conventional DC motor with the mechanical commutation replaced by an electronically controlled commutation system. These motors have the rotating permanent magnets and stationary armature. The BLDC motor that are utilized in the proposed control design is star connected BLDC motor. The power distribution is achieved by the intelligent electronic controller. The electronic controller requires rotor position information for proper commutation of currents in the respective stator windings. The rotor position can be sensed using Hall effect sensors embedded in the stator and thus stator windings are energized accordingly.

BLDC motor drive control can be done in sensor or sensor less mode. Though the 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 and algorithms makes the use of Hall sensors more efficient. Embedded control of BLDC motors using dsPIC30f4013 generates a PWM signal that controls the inverter topology there by controlling the drive. High flexibility of control can be obtained by implementing efficient control algorithm in the controller .

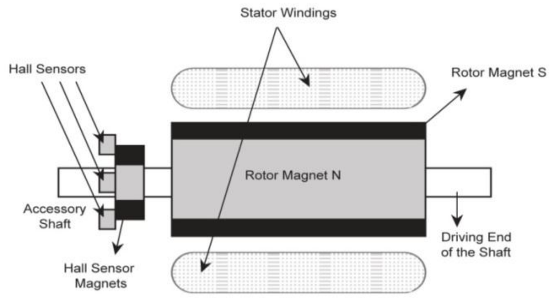


Fig.1. Bldc Motor Transverse Section with Hall Sensors

The rotor position is sensed which enables commutation logic for the three phase inverter circuits that contain MOSFET switches.

TABLE I
Clockwise Hall Sensor Signals and Drive Signals

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
0	1	1	0	1	0	0	1	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

Where H_a, H_b, H_c represents the Hall sensor signals. Q_1 - Q_6 represents the MOSFETs in the Switching circuit.

The Hall sensors should be kept 120˚ apart to obtain symmetrical operation of motor phases. With the rotor position sensed, three bit codes of Hall sensed signal is obtained as shown in TABLE I. Each code value specifies the rotor position and the corresponding stator windings that are to be energized. H_a, H_b, H_c 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 switches Q_1 - Q_6 are ON/OFF. From TABLE I it is seen that when HC is high, the switch Q_4-Q_5 conducts energizing the corresponding stator windings are energized. Digital PWM signals are generated and Speed regulation is achieved by using high and low level duty cycles.

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 linear 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. With the usage of single antecedent fuzzy rule the intersection of fuzzy rule problem can be eliminated. With the fuzzy rules designed the desired control can be achieved.

The complete drive system can be modeled with MATLAB/Simulink tool by categorizing the model into BLDC motor, switching circuit/Inverter topology, PWM driver circuit and the Controller circuit. The Fuzzy combined controllers can also be used if there exists a need to combine all local fuzzy controllers that minimizes the chattering effects and the stability is improved. Fuzzy rule bases are determined by the Fuzzy clustering methods (FCM) to obtain the membership functions that are utilized in the design of fuzzy rules for the generation of PWM pulses.

This paper describes the speed control of the BLDC motor drive designed with fuzzy logic controller that is simulated and the dynamic characteristics are obtained and analyzed using the MATLAB/Simulink Tool. This paper is organized as follows. Section II describes the mathematical model. Section III describes the Fuzzy sets and rules evaluation for Speed control of BLDC motor. Section IV describes the MATLAB/Simulink model. Section V provides the results of the Simulink model and its outputs are analyzed. Section VI concludes the system with the future prospects of the design.

II. MODEL DESCRIPTION

A. Mathematical Model of BLDC Motor Drive

In a brushless motor, the rotor incorporates the magnets, and the stator contains the windings. As the name suggests brushes are absent and hence in this case, commutation is implemented electronically with a drive amplifier that uses semiconductor switches to change current in the windings based on rotor position feedback. In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor .

The principle of operation and the dynamic model of BLDC motor can be explained as follows. The circuit equations of the stator windings in terms of electrical constants is given by equations (1)-(8)

$$v_{an} = R_a i_a + \frac{d}{dt}(L_{aa} i_a + L_{ba} i_b + L_{ca} i_c) + e_a \quad (1)$$

$$v_{bn} = R_b i_b + \frac{d}{dt}(L_{ab} i_a + L_{bb} i_b + L_{cb} i_c) + e_b \quad (2)$$

$$v_{cn} = R_c i_c + \frac{d}{dt}(L_{ac} i_a + L_{bc} i_b + L_{cc} i_c) + e_c \quad (3)$$

$$R_a = R_b = R_c = R \quad (4)$$

$$L_{aa} = L_{bb} = L_{cc} = L_s \quad (5)$$

$$L_{ba} = L_{ab} = L_{ca} = L_{ac} = L_{bc} = L_{cb} = M \quad (6)$$

$$\begin{bmatrix} V_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (7)$$

Since $i_a + i_b + i_c = 0$, and with (Ls – M) = L, we have

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (8)$$

R: Stator Resistance per phase assumed to be equal for all phases.

L_s: Stator inductance per phase assumed to be equal for all phases.

M: Mutual inductance between the phases.

i_a, i_b, i_c - Stator current /phase.

The instantaneous induced EMFs can be written as in equation (9)-(11)

$$e_a = f_a(\theta_r)\lambda_p \omega_m \quad (9)$$

$$e_b = f_b(\theta_r)\lambda_p \omega_m \quad (10)$$

$$e_c = f_c(\theta_r)\lambda_p \omega_m \quad (11)$$

Where ω_m, is the rotor mechanical speed and θ_r is the rotor electrical position.

With the rotor position being sensed the three phase switching sequence can be illustrated using Fig.2.

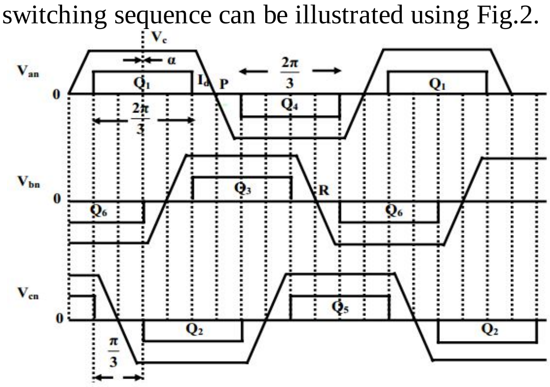


Fig.2.Three Phase Switching Sequence

The switching instant of the individual transistor switches, Q_1-Q_6 with respect to the trapezoidal EMF wave is shown in the Fig.2.It is seen that the EMF wave is synchronized with the rotor. So switching the stator phases synchronously with the EMF wave make the stator and rotor mmfs rotate in synchronism. Thus, the inverter acts like an electronic commutator that receives switching logical pulses from the rotor position sensor. This is why a BLDC drive is also commonly known as an electronically commutated motor (ECM).

B. Fuzzy Logic Controller

In recent years, fuzzy control has emerged as a practical alternative to classical control schemes when one is interested in controlling certain time varying, non-linear, and ill-defined processes. There have in fact been several successful commercial and industrial applications of fuzzy control. Fuzzy controllers are used to control consumer products, such as washing machines, video cameras, and rice cookers, as well as industrial processes, such as cement kilns, underground trains, and robots. Fuzzy control is a control method based on fuzzy logic. Fuzzy logic can be described simply as computing with words rather than numbers; fuzzy control can be described simply as control with sentences rather than equations. A fuzzy controller can include empirical rules, and that is especially useful in operator controlled plants.

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. There are two types of fuzzy inference systems that can be implemented in the fuzzy logic toolbox which are Mamdani-type and Takagi–Sugeno (T–S) type. The basic structure of a Mamdani- type F.L.C as illustrated in fig.3 below consists of the following components:

Fuzzification, which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.

Rule-Base, (a set of If-Then rules), which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control.

Inference Mechanism, (also called an "inference engine" or "fuzzy inference" module), which emulates the expert's decision making in interpreting and applying knowledge about how best to control the system.

Defuzzification Interface, which converts the conclusions of the inference mechanism into actual inputs for the process.

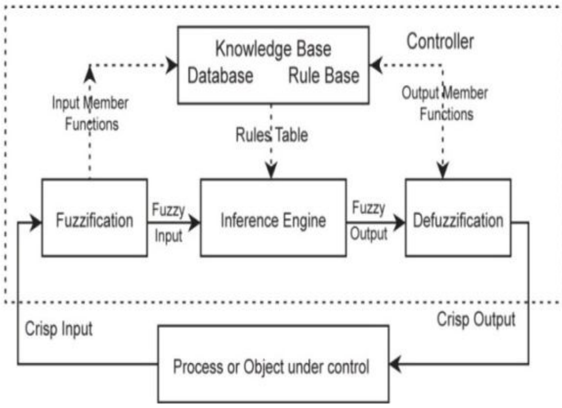


Fig.3. Basic block diagram of flc

III. Fuzzy sets and rules evaluation- Speed control of BLDC Motor drive

The basic block diagram of the speed control of BLDC motor drive using Fuzzy logic controller is illustrated in Fig.4.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.

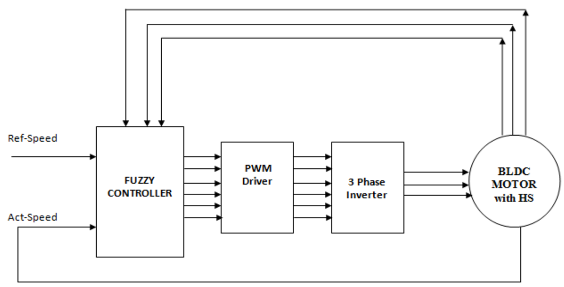


Fig.4.Block Diagram of Fuzzy Controlled Bldc Motor Drive

A. Steps in Fuzzy Decision algorithm:

Step1: The Fuzzy rules are designed and the rules that are verified are invoked using the membership functions and the truth values obtained.

Step2: The result is mapped to the membership function and the variable to control the output variable.

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.

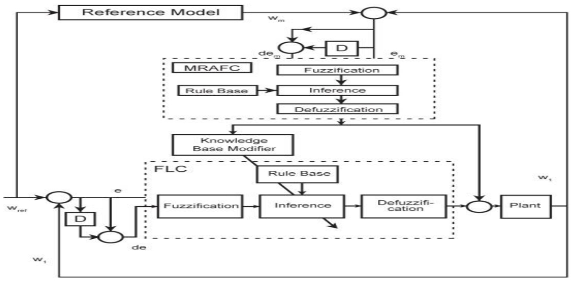


Fig.5.Flow Model Of Fuzzy Speed Reference Control

The fig.5 represents the flow model for fuzzy speed reference control.

This Fuzzy flow model describes the conversion of all crisp inputs of both the reference model and the model to be controlled into the fuzzy inputs.

The purpose of the Model Reference Adaptive Fuzzy Control (MRAFC) specified in Fig.5 is to change the rules definition in the direct fuzzy logic controller (FLC) and rule base table according to the comparison between the reference model output signal and system output. With MRAFC, good tracking characteristics were obtained even under severe variations of system parameters. The MRAFC observes the model outputs and adjusts the rules in a direct fuzzy controller, so that the overall system control capability is improved. High performances and robustness have been achieved by using the MRAFC.

B. Fuzzy Membership Functions:

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).

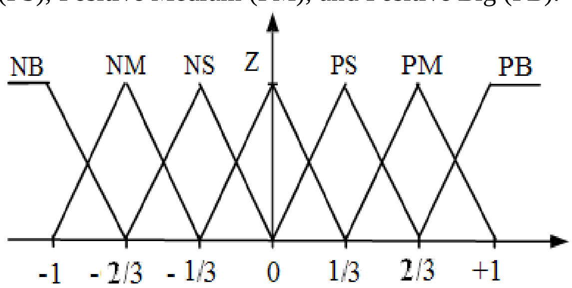


Fig.6 Membership Function Of Flc

To evaluate the disjunction of the rule antecedents the OR fuzzy operation is used. Fuzzy expert systems make use of the classical fuzzy operation union expressed in equation(12),

$$\mu_A(x) \cup \mu_B(x) = \max(\mu_A(x), \mu_B(x)) \quad (12)$$

Similarly, in order to evaluate the conjunction of the rule antecedents, the AND fuzzy operation is used and the classical fuzzy operation intersection is given by equation (13).

$$\mu_A(x) \cap \mu_B(x) = \min(\mu_A(x), \mu_B(x)) \quad (13)$$

The min-max compositional rule of inference is used. There are several defuzzification methods, in this design the centroid technique specified in Fig.7 is utilized. It finds the point where a vertical line would slice the aggregate set into two equal masses.

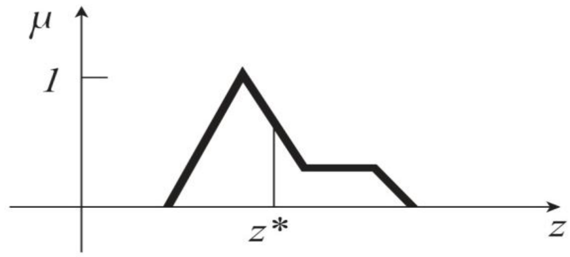


Fig.7.Centroid Defuzzification Method

Mathematically this centre of gravity (COG) can be expressed as:

$$Z^* = \frac{\sum \mu_c(\bar{z})}{\sum \mu_c(\bar{z})} \cdot \bar{z} \quad (14)$$

Where $\sum$ denotes the algebraic sum, $\bar{z}$ represents centroid of each member ship function. Thus the fuzzification, inference and defuzzification are performed using equation (14).

Fig.8 represents the fuzzy inference system of the designed fuzzy controller. Fuzzy inference system contains the input signals and output signals that provide the input membership functions and the output membership functions.

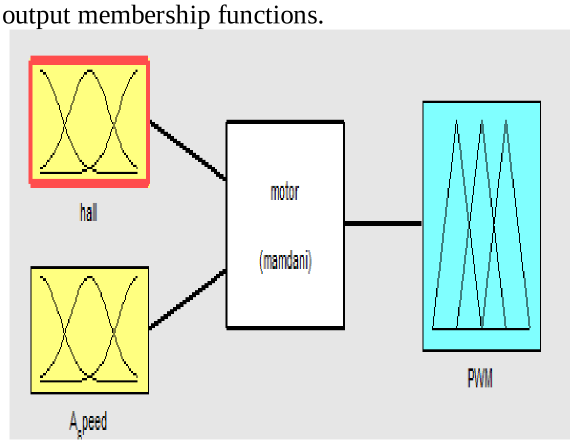


Fig.8.Fis For Speed Control Of Bldc Motor

The hall signals senses the rotor position, with the rotor position corresponding speed is detected. The desired speed of the motor is known. The inference engine specified (motor) in Fig.8contains the Fuzzy

rules that produces the corresponding PWM signals.
The input member ship function of the two inputs of the system is represented in Fig. 9 and Fig. 10. The Fuzzy system contains two input membership functions, one is the hall signal and the other is the speed signal. It contains PWM signals as one output membership function.

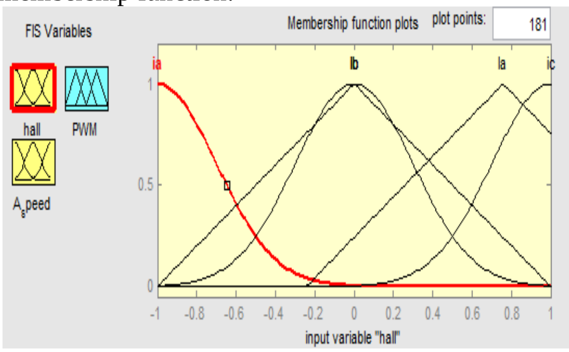


Fig.9 input membership function of hall signal

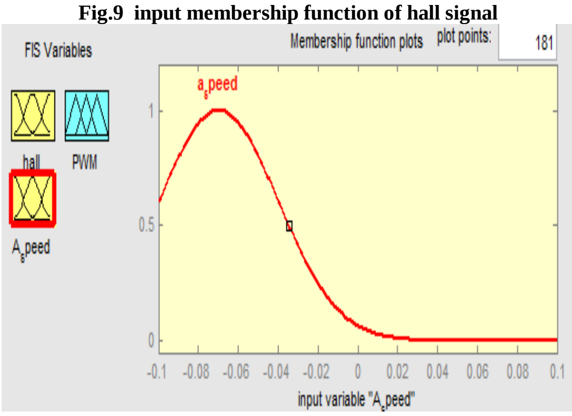


Fig. 10 input membership function of actual speed signal

The corresponding output membership functions of the PWM signals are represented in the Fig.11

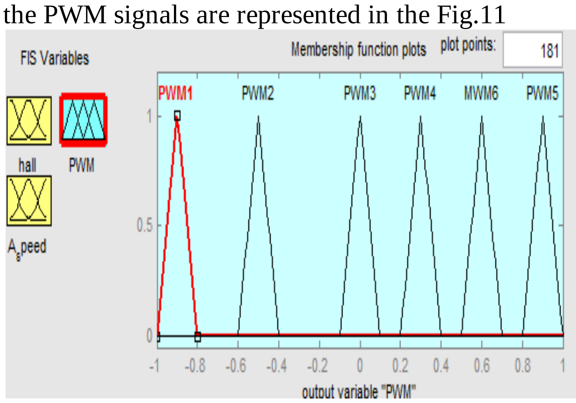


Fig.11 Output Memebership Function Of Pwm Signals

The Fuzzy Inference system is designed with the Fuzzy rules specified in the Mamdani type of FIS.With the designed fuzzy rules the PWM signals are generated that provides the necessary gate signals for the switchng of the Inverter bridge circuit that energises the respective windings of the three phase BLDC motor and hence the speed of the motor is controlled as desired.

III. SIMULINK MODEL

The developed MATLAB model in Fig.12 provides the speed control of BLDC Motor using Fuzzy logic controller. The simulation results provide the necessary waveforms for the analysis of speed control of BLDC motor drives.

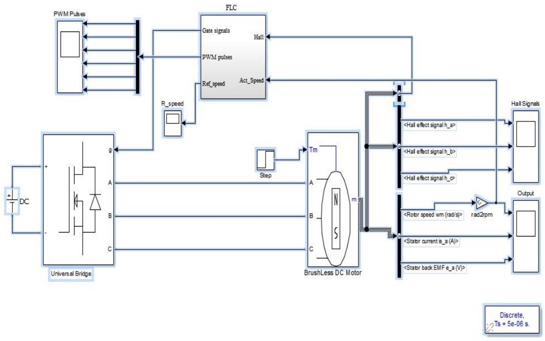


Fig.12.matlab/simulink model of bldc motor using fuzzy logic controller.

The implemented Fuzzy rules provide the following waveforms in the speed control of BLDC Motor drive.

IV. RESULTS AND DISCUSSION

The Hall sensor signals that is the signals with respect to the rotor position of the BLDC motor are generated. In reference to these Hall signals the PWM signals are generated. The PWM signals generated provide the control signals for the switching circuits that energize the stator windings accordingly and the actual speed of the motor is varied with respect to the reference speed.
The reference speed of the BLDC motor is seen in the oscilloscope as in Fig.15.

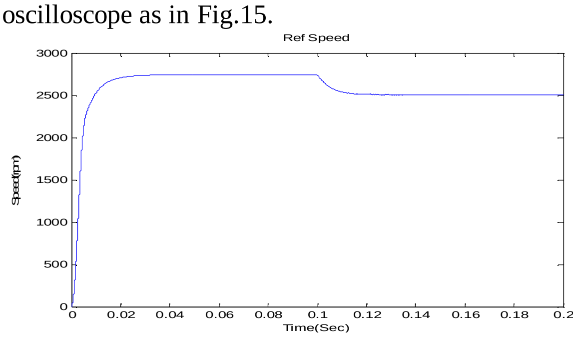


Fig.15. Reference speed of bldc motor drive

The speed of the motor with Fuzzy logic controller is seen as in Fig.16.

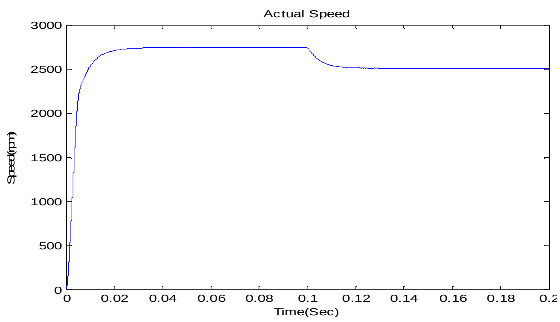
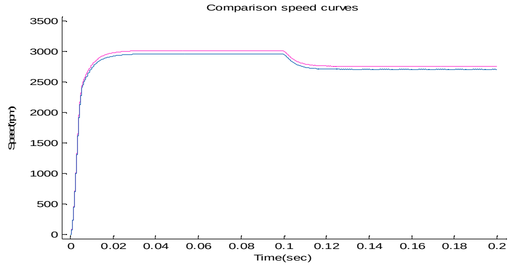


Fig.16.Speed Of Bldc Motor Using Fuzzy Controller

The results obtained shows that the actual speed is approximately equal to the reference speed. Thus an efficient speed control is achieved, for a BLDC Motor using Fuzzy Logic Controller. The comparison curves of the actual speed and reference speed obtained using the simulation inspector tool is illustrated as in Fig.17



REF.SPEED, ACTUAL SPEED
Fig.17.comparison of refernce and actual speed curves

With the graph obtained it is observed that the efficiency of the designed Fuzzy Logic Controller is calculated as 98.1% which proves to be efficient than the conventional controllers.

CONCLUSION

In this paper the control scheme for the speed control of BLDC motor using Fuzzy logic controller is proposed. The significant advantages of the proposed work are: (1) simplicity of control i.e. the fuzzy rule base or Fuzzy set can be easily modified (2) Increased robustness. The simulation of Fuzzy Logic controller, using MATLAB to control the speed of flexible BLDC Motor, proves that the desired speed is attained with a shorter response time, when compared with conventional controllers. The dynamic characteristics of the motor is obtained and the analysis reveals that Fuzzy controller is a highly controller and is capable of controlling the motor drive over wide speed range. The fuzzy controller proves to be more efficient than the conventional controller. The simulated Fuzzy control will be implemented, using dsPIC30F4013. A prototype model will be developed to analyze characteristics and the hardware results will be compared with the results of conventional controllers.

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