# CLOSED LOOP CONTROLLER BRUSHLESS PERMANENT MAGNET MOTOR WITH FUZZY CONTROLLER

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***ABSTRACT :*** ***This paper focuses on a low cost speed control system using a fuzzy logic controller for a Brushless DC Motor. In a digital controller of brushless DC Motor, the control accuracy is of a high level, and it has a fast response time. We designed the fuzzy logic controller and implemented the speed control system of brushless DC Motor, to acquire an accurate fuzzy logic control algorithm. Based on the mathematical model of BLDC motor, a novel fuzzy method is proposed for controlling the speed servo system. In the BLDC motor speed control system, the current hysteresis is implemented in the current loop, in the speed loop the P and fuzzy control scheme is applied. The proposed system uses an adaptation of the slope of the membership functions of the variables used in the conventional fuzzy controller based on the magnitude of the error. A simulation analysis of the fuzzy controller and the adaptive fuzzy controller are done and their performances are compared and simulation results of fuzzy controller is presented.***

***IndexTerms - BLDC motor, fuzzy logic controller.***

## I. *INTRODUCTION*

Recently, a brushless DC Motor (BLDC) has been rapidly demanded due to preciseness of industrial technology and increase of various kind of control device. Because a brushless DC Motor is suitable as a servo motor because of its high efficiency and excellent control character. So, we designed a low cost controller for brushless DC Motor, with high rely on quality. A PMBLDC motor is inside out construction of DC motor. The efficiency is likely to be higher than DC motor of equal size and the absence of commutator and brushes, reduces the motor length. Hence the lateral stiffness of the motor is increased, allowing for high speeds [1, 2]. The power electronic converters required in brushless dc motor are similar in topology to the PWM inverter used in induction motor drives.

Nowadays brushless dc motors are used in various applications such as defense, industries, robotics, etc. In these applications, motor should be precisely controlled so as to give desired performance. The classical controller need accurate mathematical model of the system and can perform well only under linear condition. Since the PMBLDC motor is highly coupled non-linear multivariable system, it is difficult to obtain its accurate mathematical model.

Hence there is a need for intelligent controller. So an attempt is made to develop fuzzy controller for PMBLDC motor. The fuzzy logic controller (FLC) is indeed capable of providing the high accuracy required by high performance drive system without the need of mathematical model [3, 4]. FLC accommodates non-linearity without utilization of mathematical model [5, 6]. The fuzzy logic controller uses fuzzy logic as a design methodology, which can be applied in developing nonlinear system for embedded control. Simplicity and less intensive mathematical design requirements are the most important features of the FLC. In fuzzy set theory, the transition between membership and non-membership can be gradual. Therefore, boundaries of fuzzy sets can be vague and ambiguous, making it useful for approximate systems. Fuzzy Logic controller is an attractive choice when precise mathematical formulations are not possible [7, 8].

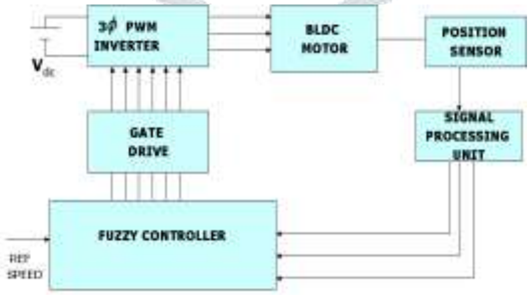


Figure 1 shows the block diagram of proposed system. The system above is composed of brushless dc motor, six step inverter, gate drive for inverter, fuzzy controller and switching logic. Due to the presence of parameter variation and load disturbance in a BLDC motor, closed loop control is necessary, to obtain a desirable behavior. BLDC motor has three phase windings on stator and Permanent Magnet on rotor. In order to define the shaft position, rotor position sensor is necessary. The sensor senses the rotor shaft position and signals. The processed signals are given to the fuzzy controller. The output of the controller is used to provide switching signals for the inverter from which the speed of the motor can be controlled.

## II. *MATHEMATICAL MODELLING*

Brushless DC Motors are permanent magnet motors where the function of commutator and brushes were implemented by solid state switches. BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. Because of the special structure of the motor, it produces a trapezoidal back electromotive force (EMF) and motor current generate a pulsating torque.

Three phase BLDC motor equations

$$Va=iaRa+La\frac{dia}{dt}+Mab\frac{dib}{dt}+Mac\frac{dic}{dt}+ea \quad \textbf{(1)}$$

$$Vb=ibRb+Lb\frac{dib}{dt}+Mba\frac{dia}{dt}+Mbc\frac{dic}{dt}+eb \quad \textbf{(2)}$$

$$Vc=icRc+Lc\frac{dic}{dt}+Mcb\frac{dib}{dt}+Mca\frac{dia}{dt}+ec \quad \textbf{(3)}$$

R: Stator resistance per phase, assumed to be equal for all phases L: Stator inductance per phase, assumed to be equal for all phases. M: Mutual inductance between the phases. ia,ib,ic: Stator current/phase. Va,Vb,Vc: are the respective phase voltage of the winding. The stator self-inductances are independent of the rotor position, hence: La=Lb=Lc=L and the mutual inductances will have the form: Mab=Mac=Mbc=Mba=Mca=Mcb=M. Assuming three phase balanced system, all the phase resistances are equal: Ra=Rb=Rc=R. Rearranging the above equations

$$Va=iaR+L\frac{dia}{dt}+M\frac{dib}{dt}+M\frac{dic}{dt}+ea \quad \textbf{(4)}$$

$$Vb=ibR+L\frac{dib}{dt}+M\frac{dia}{dt}+M\frac{dic}{dt}+eb \quad \textbf{(5)}$$

$$Vc=icR+L\frac{dic}{dt}+M\frac{dib}{dt}+M\frac{dia}{dt}+ec \quad \textbf{(6)}$$

Neglecting mutual inductance

$$Va=iaR+L\frac{dia}{dt}+ea \quad \textbf{(7)}$$

$$Vb=ibR+L\frac{dib}{dt}+eb \quad \textbf{(8)}$$

$$Vc=icR+L\frac{dic}{dt}+ec \quad \textbf{(9)}$$

### *III. TRAPEZOIDAL BACK EMF*

When a BLDC motor rotates, each winding generates a voltage known as back Electromotive Force or back EMF, which opposes the main voltage supplied to the windings according to Lenz's Law. The polarity of this back EMF is in opposite direction of the energized voltage. Back EMF depends mainly on three factors: Angular velocity of the rotor, Magnetic field generated by rotor magnets.The number of turns in the stator windings. Once the motor is designed, the rotor magnetic field and the number of turns in the stator windings remain constant. The only factor that governs back EMF is the angular velocity or speed of the rotor and as the speed increases, back EMF also increases. The potential difference across a winding can be calculated by subtracting the back EMF value from the supply voltage. The motors are designed with a back EMF constant in such a way that when the motor is running at the rated speed, the potential difference between the back EMF and the supply voltage will be sufficient for the motor to draw the rated current and deliver the rated torque. If the motor is driven beyond the rated speed, back EMF may increase substantially, thus decreasing the potential difference across the winding, reducing the current drawn which results in a drooping torque curve. In general, Permanent Magnet Alternating current (PMAC) motors are categorized into two types. The first type of motor is referred to as PM synchronous motor (PMSM).

These produce sinusoidal back EMF and should be supplied with sinusoidal current / voltage. The second type of PMAC has trapezoidal back EMF and is referred to as the Brushless DC (BLDC) motor. The BLDC motor requires that quasi-rectangular shaped currents are to be fed to the machine. When a brushless dc motor rotates, each winding generates a voltage known as electromotive force or back EMF, which opposes the main voltage supplied to the windings. The polarity of the back EMF is opposite to the energized voltage. The stator has three phase windings, and each winding is displaced by 120 degree. The windings are distributed so as to produce trapezoidal back EMF. The principle of the PMBLDC motor is to energize the phase pairs that produce constant torque. The three phase currents are controlled to take a quasi-square waveform in order to synchronize with the trapezoidal back EMF to produce the constant torque. The back EMF is a function of rotor position (θ) and has the amplitude E= Ke* ω (Ke is the back EMF constant).
The instantaneous back EMF in BLDC is written as:

$$Ea= fa(\theta)*Ka*\omega \quad \textbf{(10)}$$

$$Eb = fb(\theta)*Kb*\omega \quad \textbf{(11)}$$

$$Ec= fc(\theta)*Kc*\omega \quad \textbf{(12)}$$

Where, "ω" is the rotor mechanical speed and "θ" is the rotor electrical position. The modelling of the back EMF is performed under the assumption that all three phases have identical back EMF waveforms. Based on the rotor position, the numerical expression of the back EMF can be obtained Therefore, with the speed command and rotor position, the symmetric three-phase back EMF waveforms can be generated at every operating speed. The respective back EMF in the windings is represented by the equations.

$$\begin{aligned} ea &= (6E/\pi)\theta && (0<\theta<\pi/6) \\ &= E && (\pi/6<\theta<5\pi/6) \\ &= -(6E/\pi)\theta+6E && (5\pi/6<\theta<7\pi/6) \\ &= -E && (7\pi/6<\theta<11\pi/6) \\ &= (6E/\pi)\theta-12E && (11\pi/6<\theta<2\pi) \end{aligned} \tag{13}$$

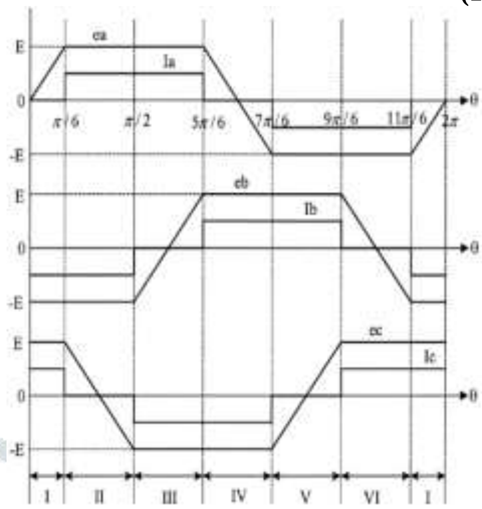

Fig.2 Back EMF and phase currents waveforms of BLDC

The quasi-square trapezoidal back EMF waveform and the phase current of the PMBLDC motor with respect to the rotor position is shown in the figure The graph is presented for one complete cycle rotation of 360 degrees.

***TORQUE GENERATION***

The Torque is the product of the theoretical motor constant Kt the supplied current" I". In a single pole system, usable torque is only produced for 1/3 of the rotation. To produce useful torque throughout the rotation of the stator, additional coils, or "phases" are added to the fixed stator. The developed torque by each phase is the product of the motor constant Kt and the current I. The sum of the torques is Ta + Tb + Tc. Assumption made is all the phases are perfect symmetry Kt(motor)=Kt(a)=Kt(b)=Kt(c). imotor = ia= ib = ic. At any given angle θ, the applied torque as measured on the rotor shaft is Tmotor = 2*Kt(motor) *imotor. The key to effective torque and speed control of a BLDC motor is based on relatively simple torque and back EMF equations, which are similar to those of the DC motor.

The generated electromagnetic torque is given by Te = [eaia + ebib + ecic] / ω (in N.m).

The electromagnetic torque is also related with motor constant and the product of the current with the electrical rotor position which is given as

$$Te = Kt\{ fa(\theta)\, ia + fb(\theta)\, ib + fc(\theta)\, ic\}$$

The equation of motion for simple system is,

$$J(d\omega/dt) + B\omega = Te - Tl$$

Where, Tl is the load torque, J is motor inertia, B is damping constant. The relation between angular velocity and angular position (electrical) is given by

$$d\theta/dt = (P/2) * \omega$$

Where, P is numbers of Poles.

***IV. INTRODUCTION TO FUZZY LOGIC CONTROLLER***

A new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to dc-to-dc converter system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of dc-to-dc converter and performance of proposed controllers. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of dc-to-dc converters.

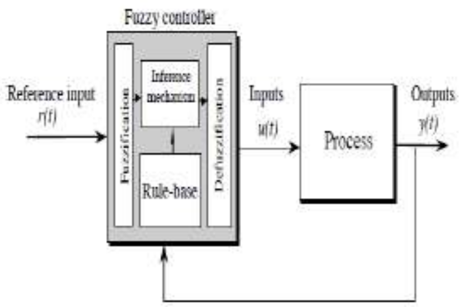


Fig.3. General structure of the fuzzy logic controller on closed-loop system

The basic scheme of a fuzzy logic controller is shown in Fig 5 and consists of four principal components such as: a fuzzy fication interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action. The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model. Simulation is performed in buck converter to verify the proposed fuzzy logic controllers.

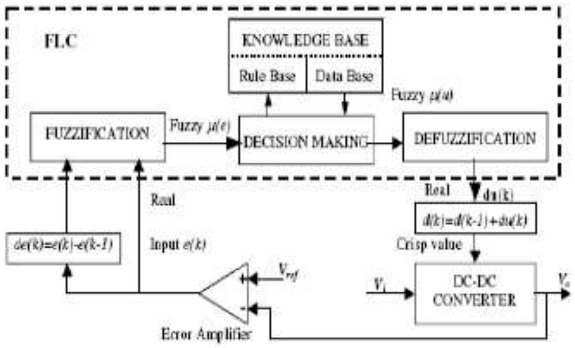


Fig.4. Block diagram of the Fuzzy Logic Controller (FLC) for dc-dc converters

### *A. FUZZY LOGIC MEMBERSHIP FUNCTIONS*

The dc-dc converter is a nonlinear function of the duty cycle because of the small signal model and its control method was applied to the control of boost converters. Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying operating points. Fuzzy Logic Controller is designed to control the output of boost dc-dc converter using Mamdani style fuzzy inference system. Two input variables, error (e) and change of error (de) are used in this fuzzy logic system. The single output variable (u) is duty cycle of PWM output.

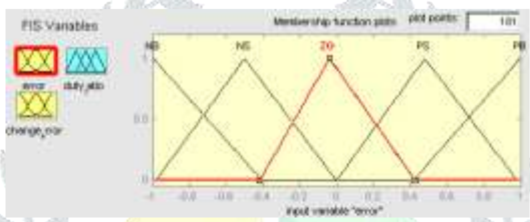


Fig. 5.The Membership Function plots of error

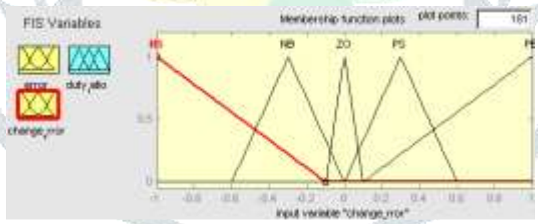


Fig.6 The Membership Function plots of change error

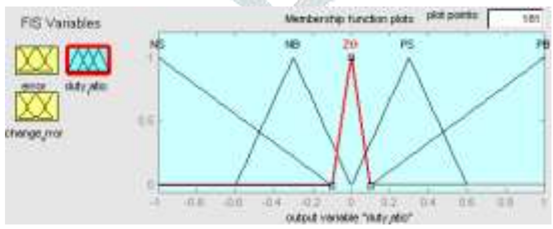


Fig.7 The Membership Function plots of duty ratio

### *B. FUZZY LOGIC RULES*

The objective of this dissertation is to control the output voltage of the boost converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into five groups; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big and its parameter. These fuzzy control rules for error and change of error can be referred in the table that is shown in Table I as per below:

Table I Table rules for error and change of error

| (de) \ (e) | NB | NS | ZO | PS | PB |
|---|---|---|---|---|---|
| NB | NB | NB | NB | NS | ZO |
| NS | NB | NB | NS | ZO | PS |
| ZO | NB | NS | ZO | PS | PB |
| PS | NS | ZO | PS | PB | PB |
| PB | ZO | PS | PB | PB | PB |

***V. MATLAB MODELING AND SIMULATION RESULTS***

Here Simulation is carried out in different cases, in that 1) Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition. 2) Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Variable Speed Condition.

***Case 1: Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition***

Fig.8 Matlab/Simulink Model of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition using Matlab/Simulink.

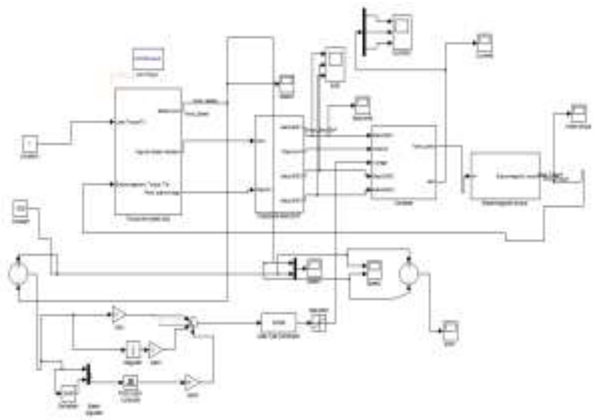

Fig.8 Matlab/Simulink Model of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition.

Fig.9 shows the three phase stator currents of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition.

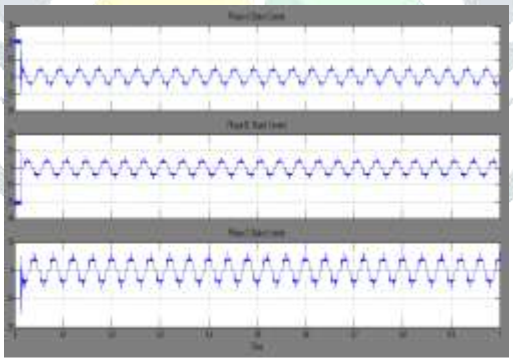

Fig.9 Three Phase Stator Currents

Fig.10 shows the three phase back emf of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition.

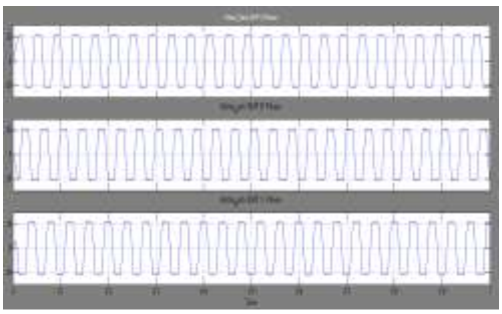

Fig.10 Three Phase Back EMF

Fig.11 shows the Electromagnetic Torque of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition.

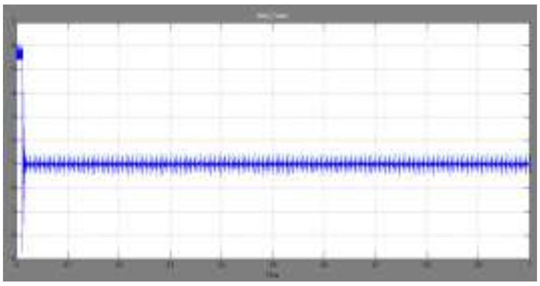

Fig.11 Electromagnetic Torque

Fig.12 shows the Reference & Actual Speeds of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition.

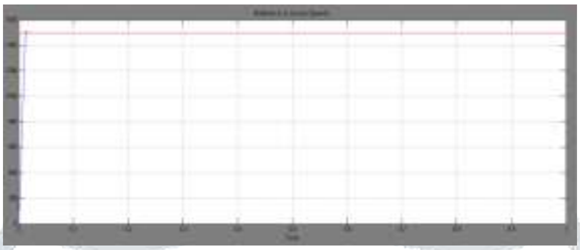

Fig.12 Reference & Actual Speeds

***Case 2: Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Variable Speed Condition***

Fig.13 Matlab/Simulink Model of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Variable Speed Condition using Matlab/Simulink.

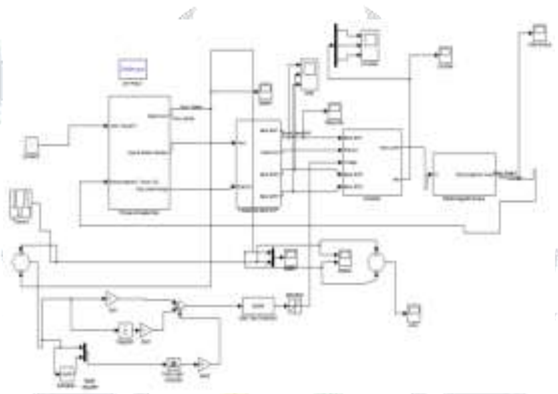

Fig.13 Matlab/Simulink Model of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Variable Speed Condition.

Fig.14 shows the three phase stator currents of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Variable Speed Condition.

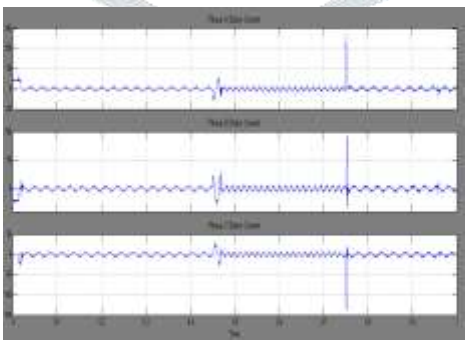

Fig.14 Three Phase Stator Currents

Fig.15 shows the three phase back emf of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Variable Speed Condition.

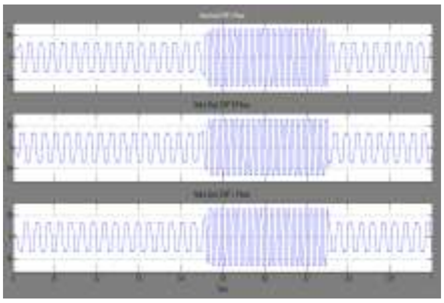

Fig.15 Three Phase Back EMF

Fig.16 shows the Electromagnetic Torque of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Variable Speed Condition.

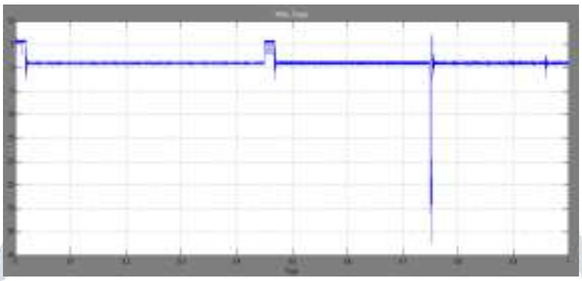

Fig.16 Electromagnetic Torque

Fig.17 shows the Reference & Actual Speeds of Closed Loop Operation of Brushless Permanente Magnet Motor with Fuzzy Controller under Fixed Speed Condition.

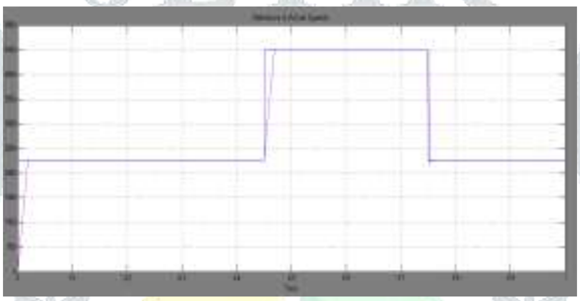

Fig.17 Reference & Actual Speeds

***VI. CONCLUSION***

Motor drive systems fed by pulse-width modulation voltage source inverters (PWM-VSIs) are widely used in industrial applications for variable-speed operation, such as aeronautics, railway traction and robotics. The wide use of the VSIs is due to the high switching frequency of the semiconductors and the use of the PWM speed controllers. This paper presents closed loop control of Permanent-magnet brushless dc motors are used in high-performance applications because of their higher efficiency, higher torque in low-speed range, high power density, low maintenance and less noise than other motors. Finally closed loop speed control BLDC is carried out and simulation results are presented. The closed loop performance of proposed drive technique using fuzzy logic controller with best results show that this modeling is very useful in studying the high performance drive before taking up the dedicated controller design concept for evaluation of dynamic performance of the motor with different loading conditions such as fixed and variable conditions using Matlab/Simulink.

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