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Brushless Dc Motor Speed Control Using Proportional-Integral And Fuzzy Controller

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Abstract : *This paper demonstrates the detailed analysis of Proportional-Integral (PI) controller and Fuzzy Logic controller for speed control of a Permanent Magnet Brushless DC (PMBLDC) motor for different speed commands and varying load torque conditions. Implementation of PI controller in closed loop conditions is done. Analysis of classical tuning methods to obtain best PI parameters for speed control is calculated. Fuzzy controller is also implemented for the same and the simulation results obtained for both PI and Fuzzy control in MATLAB/Simulink are compared. PI controllers have poor response due to overshoot, more drop in speed and oscillations. Intelligent control like Fuzzy Logic is gaining momentum as it can overcome these disadvantages. Microcontroller based controller implementation is tested using a virtual motor and the results or PI controller are validated using software results.*

Keywords**–** *BLDC, Fuzzy logic controller, PI controller, PWM and virtual motor*

I. INTRODUCTION

1.1. Brushless Dc Motor

BLDC motors have electronic commutator, instead of brushes, thus they have higher efficiency, long operating life, rugged construction and noiseless operation. BLDC motor implements the basic principle of conventional DC motors except that the stator has three phase windings whereas the rotor has pole magnets. The hall sensors embedded in the motor detects the rotor position. The decoder decodes the position of the rotor and produces gate pulses to trigger the six-switch inverter to produce AC voltage that energizes the stator windings to produce current.

1.2. Review of Literature

Several investigations on BLDC motor are reported. In 2003, Padmaraja Yedamale [23], concluded that BLDC motors have advantages over brushed DC motors and induction motors. In 2009, Bhim Singh [7] did an exhaustive overview of PMBLDCM drives. In 2010, A. Ahfock and D. Gambetta [1] presented a paper about sensorless commutation of BLDC motor by equal inductance method. In 2006, Dae-Kyong Kim, Kwang-Woon Lee, and Byung-Il Kwon [10] proposed a torque ripple reduction method for a position sensorless BLDC motor drive. In 2011, Dawid Makiela [11] examined sensorless high-speed PM BLDC motor control methods for a particular target speed. In paper [24], [29], the speed control of position sensorless brushless DC motor is discussed. In 2009, K. Wang et al [18] studied the design of high-speed brushless DC motors equipped with surface-mounted magnets, for sensorless operation based on the third harmonic back-EMF.

In 2010, A. Rahideh et al [4] presented a method for the optimal design of a slotless PMBLDC motor with surface mounted magnets using a genetic algorithm. Intelligence control like generic control has paved way for increased control and accuracy. In 2002, Bhim Singh and Sanjeev singh [6] presented a new speed control strategy of a PMBLDC motor drive. In 2011, Cassio Luciano et al presented a paper [9] on speed control for BLDC compressor using a repetitive plug-in control with variable sampling period. In paper [2] and [13], torque controller system for a BLDC motor is analysed.

Bogdan Alecsa and Alexandru Onea [8] presented a paper to implement a digital BLDC motor speed controller inside an FPGA device. In 2007, Eric Monmasson and Marcian N. Cirstea [12] presented a paper on the contributions of FPGAs to the control of industrial systems. In 2010, Wang Xing-gui and Liu Qi [25] suggested a robust position control of the PMBLDCM. In 2011, Hao Chen, Song Sun, Dionysios C. Aliprantis, and Joseph Zambreno [14] presented the FPGA implementation of an induction machine dynamic simulation, using numerical integration algorithm. In 1999**,** Z. M. Zhao, S. Meng and X N.Yue [30] developed and implemented a virtual system integrating software with hardware in loop and implemented for motor drive applications.

In 2012, Jiancheng Fang, Haitao Li and Bangcheng Han [15] proposed a new PWM current control method. In 2006, Jianwen Shao [16] presented the improved direct back-EMF-sensing scheme that eliminates duty-cycle limitation by adding the option of sensing the back EMF during the high-side-switch PWM on time. In 2006, Maurício Beltrão et al [20] presented a method to generate PWM signals for control of four-switch three-phase inverters. In 2004, Yen-Shin Lai, Fu-San Shyu, and Yung-Hsin Chang [27] presented a new PWM technique for brushless dc motor drives fed by MOSFET inverter, which significantly reduces the conduction losses and especially becomes very promising for small power applications. In 2010, A Albert Rajan et al [3] presented an idea to replace the conventional constant frequency digital PWM control method for speed variation in BLDC by variable frequency and variable duty ratio fuzzy logic method.

In 2003, J. X. Shen and K. J. Tseng [17] presented equations to calculate the error, which is related to the motor parameters and load. In 2005, Mohamed A. Awadallah et al [21] presented two independent schemes for automatic fault diagnosis and location of inter-turn short circuits on the stator winding of CSI-fed PM brushless dc motors. In 2010, K. Wang, M. A. Rahman and J. X. Shen [19] presented a paper on pertinent design aspects related to enhancing the third harmonic back- EMF, mainly from the stator topology. In 2007, WU Chun-hua, CHEN Guo-cheng and Sun Cheng [26] presented an idea to eliminate the expensive hall sensor method to detect rotor position and introduced wide-angle wave control method for the same.

In 2011, M. V. Rameshet al [22] presented a paper for PI and fuzzy logic controller for speed control of BLDC motor.. In 2010, Baharuddin Ismail and Tan Chee Siong [5] compared Proportional-Integral (PI) controller and fuzzy logic controller for speed control. In 2010**,** Ying Gao, Dedi Chen and Rong Wang [28] applied fuzzy control theory to the speed regulating system of BLDCM, based on the mathematical model. As surveyed, the latest research lacks variety in speed controlling techniques. This paper includes the designing of PI as well as fuzzy logic intelligent control, with varying load torques and changing speed references. Three PI tuning methods are attempted. Both Mamdani and Sugeno inference models in fuzzy are overviewed. Successful implementation of controller is done with the help of microcontroller.

1.3. BLDC Motor modelling equations

The dynamic equations of BLDC are as follows:

$$\mathrm{Van}(t) = ia(t)Ra + La\frac{dia(t)}{dt} + ea(t) \qquad (1)$$

$$\mathrm{Vbn}(t) = ib(t)Rb + Lb\frac{dib(t)}{dt} + eb(t) \qquad (2)$$

$$\mathrm{Vcn}\,(t) = ic(t)Rc + Lc\frac{dic(t)}{dt} + ec(t) \qquad (3)$$

$$\mathrm{Tem}(t) = J\frac{dw(t)}{dt} + TL + N\omega(t) \qquad (4)$$

$$T=k_{\phi}I \qquad (5)$$

$$E=k_{\phi}\tilde{\omega}$$

1.4. Open loop condition

Parameter of BLDC motor drive system used for simulation purpose is as shown in TABLE 1

Table 1 motor parameters

Armature Resistance (Ra)	10.5Ω
Armature Inductance(La)	43mH
Back Emf constant (K_{Φ})	0.525V/rad/sec
Mechanical Inertia(J)	0.000085kg m^2
Friction Coeficient(B)	0.0002073Nm/rad/sec

For simulation purpose, two pole permanent magnet rotor is incorporated. When load torque is applied in open loop the speed decreases and as there is no control action, the speed cannot recover to its rated value. Fig. 1 shows speed at varying load torques.

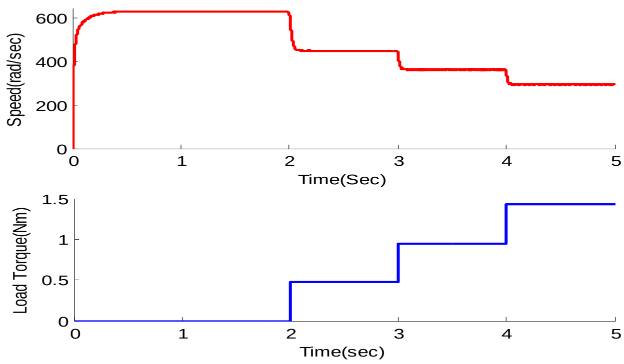


Figure 1 Speed at varying load torques

The speed needs to go back to its rated value after load torque is applied to suffice its rated speed requirement in industrial applications.

II. Closed Loop Speed Control Using Pi Controller

2.1 PI controller

Two controllers are incorporated: PI controller for speed control and P controller for current control. As shown in Fig. 2 the feedback measures the actual speed and subtracted from reference speed and error is given as input to the speed PI controller and output of the PI is subjected to current limiter and that acts as current reference from which actual current is subtracted and error is given input to the current P controller. This output of the PI is the dc value that is compared with a continuous triangular pulse of 40 kHz. The output is varying duty cycle that is anded with gate pulse to produce a pulse-modulated wave, which triggers the inverter to generate required voltage to maintain the speed at varying load torques and speed reference conditions.

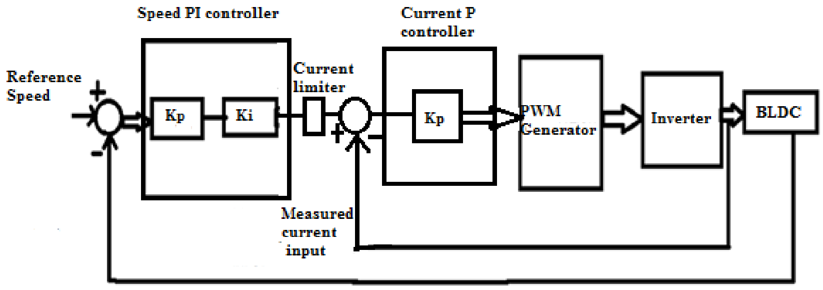


Figure 2 Closed loop PI for speed control

2.2 Simulation results

Three PI tuning methods were performed for speed control and parameters obtained are shown in Table 2.

TABLE 2 Comparison of three PI tuning methods

METHODS	Kp	Ki	OVERSHOOT (%)	DROP IN SPEED (rad/sec)	Settling Time (sec)
Ziegler Nichols Open Loop	0.18	101.5	3.45	5.2	0.3
Ziegler Nichols Closed Loop	0.136	24.4	3.1	6.8	0.25
Cohen Coon	0.15	40	2.97	4.8	0.2

Cohen coon method K_p and K_i values were chosen as it has the least drop in speed, less overshoot and less settling time. The simulation is performed in closed loop when speed reference is constant at 628.32 rad/sec and load torque changes from 0.475 Nm to 0.95 Nm and then back to 0.475Nm as shown in Fig.3. The stator currents during transition states is as shown in Fig.4.

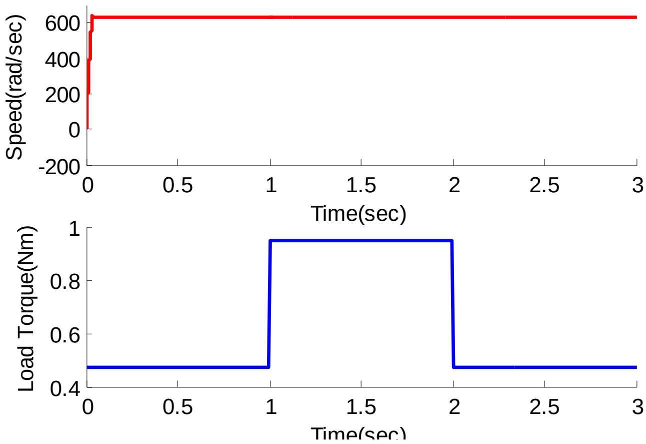


Figure 3 Speed when load torque changes

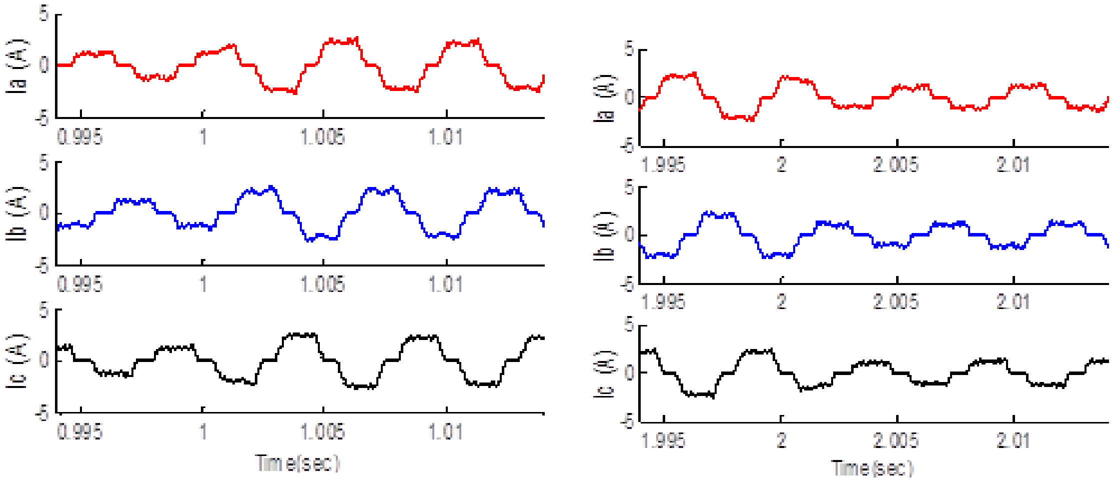


Figure 4 Stator current at transition states

The simulation is then performed in closed loop with constant load torque of 1.425Nm and changing speed reference from 100 to 500 rad/sec as shown in Fig.5.

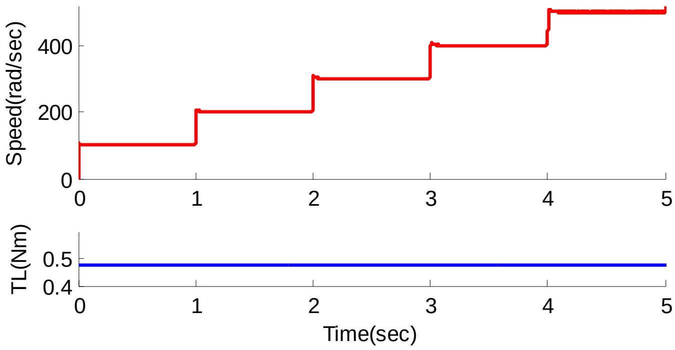


Figure 5 Change in reference speed at constant load torque

III. Closed Loop Speed Control Using Fuzzy Controller

3.1. Fuzzy logic

Fuzzy logic provides a medium to represent imprecision and vague values in terms of linguistic constructs. Fig. 6 shows a fuzzy logic diagram with two error inputs and one output. The crisp error values given to the fuzzy inference system follows three steps. First, the crisp values are fuzzified to give relatively graded membership values. Secondly, rule set contained in the fuzzy rule based system takes decision to produce an output. Thirdly, this output value is defuzzified to deliver crisp outputs. Defuzzification types like max-min membership, weighted average, centroid method, etc. can be used. Membership functions like triangular, trapezoidal, Gaussian can be incorporated.

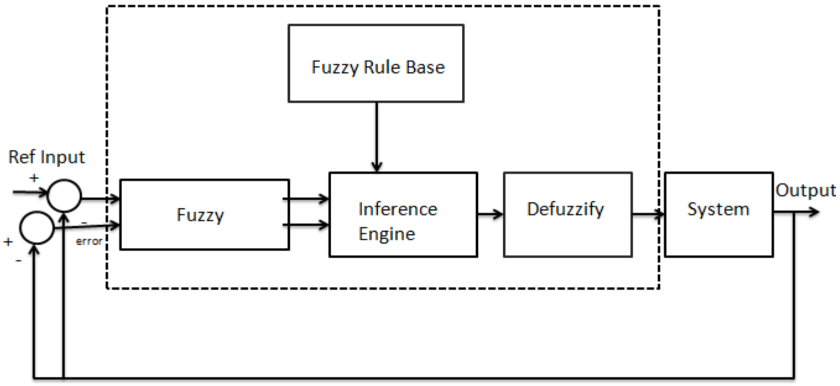


Figure 6 Block diagram of Fuzzy Logic

Fig. 7 shows the closed loop block diagram using fuzzy logic controller with two error input speed errorand current error.

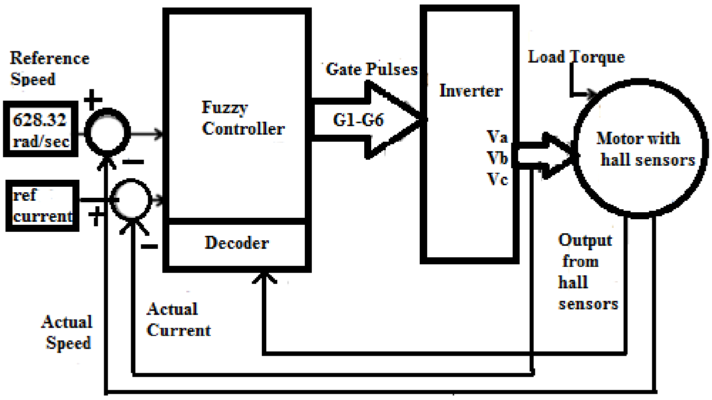


Figure 7 Closed loop Fuzzy speed controller

3.2. Fuzzy logic structure

In the proposed fuzzy speed controller for BLDC, two inputs are defined: current error (three Gaussian membership functions i.e. S,Z and L) as shown in Fig. 8 and speed error(seven Gaussian membership functions i.e. NB,NM,NS,Z,PS,PM and PB) as shown in Fig. 9. The current error range varies from 0 to 1.45 A, whereas, the speed error range varies from -630 to 630 rad/sec.

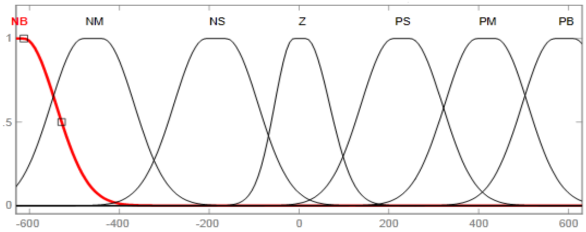


Figure 8 Input 1 Speed error membership functions functions

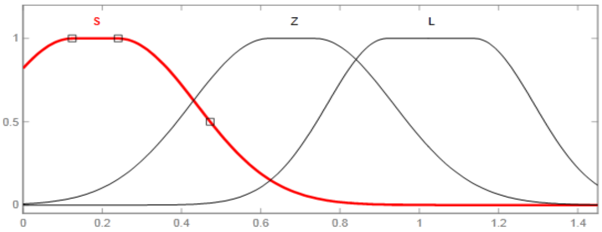


Figure 9 Input2 is current error membership

The output of the Mamdani inference model is a Gaussian membership function varying from 0.59 to1 with nine membership functions i.e. NVB, NB, NM, NS, Z, PS, PM, PB and PVB) as shown in Fig10.The output is a duty cycle that is compared with a triangular pulse to generate pulse width modulated signal, which is further anded with the gate pulses to modulate the inverter voltage and maintain a constant speed. The rule set followed is shown in Table 3.

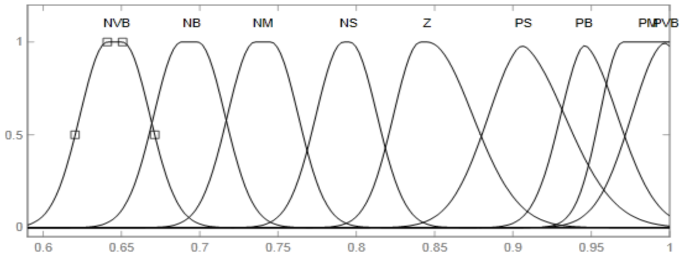


Figure 10 Output membership functions

TABLE 3 Fuzzy rule table

CE/SE	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
S	NVB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
L	NM	NS	Z	PS	PM	PB	PVB

3.3. Simulation results

The simulation is performed in closed loop when speed reference is constant at 628.32 rad/sec and load torque changes from 0.475 Nm to 0.95 Nm and then back to 0.475Nm as shown in Fig. 11. The stator currents during transition are as shown in Fig.12.

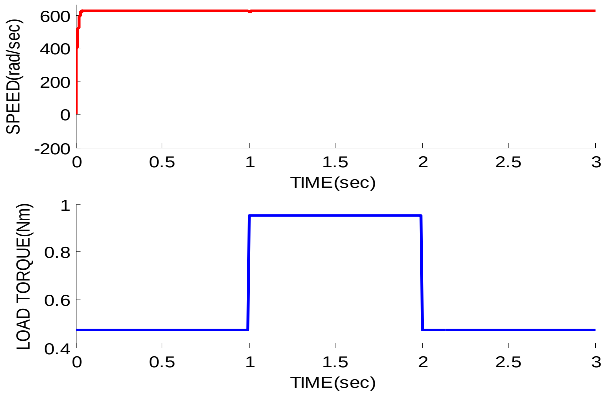


Figure 11 Speed when load torque decreases

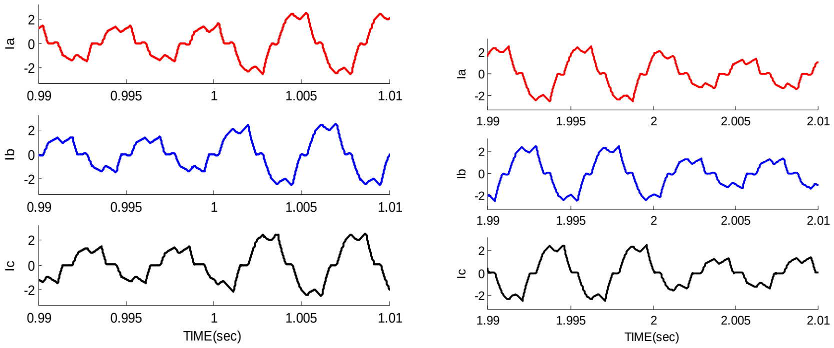


Figure 12 Current at transition states

The simulation is the performed in closed loop with constant load torque of 1.425Nm and changing speed reference from 100 to 500 rad/sec as shown in Fig.13.

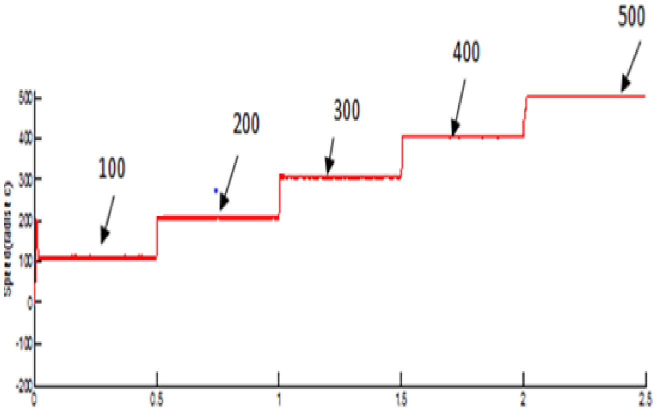


Figure 13 Speed when speed reference is varied

At a constant load torque of 1.425 Nm, speed at various reference speed is obtained using Sugeno inference model. As mentioned in the above Mamdani model, two inputs are taken, current error and speed error. They are triangular membership types. The Sugeno output is in the form of duty cycle which generates pulse-modulated signal and hence output voltage is varied according to the errors fed back to the controller.

IV. COMPARISION OF PI CONTROLLER AND FUZZY CONTROLLER

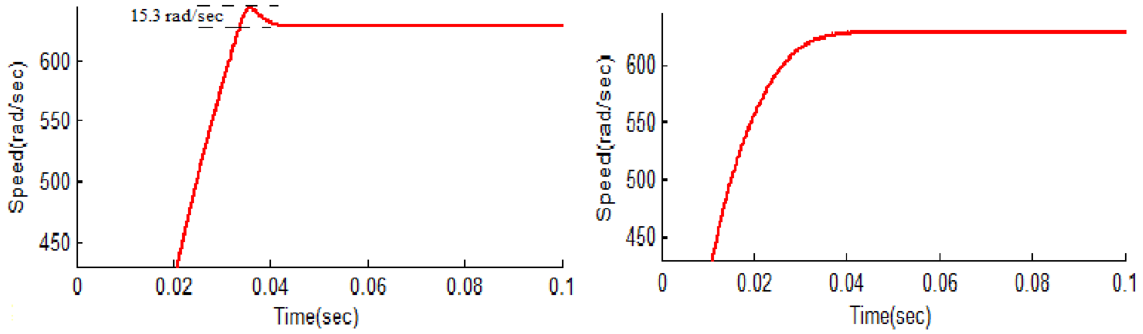


Figure 14 Speed at starting condition

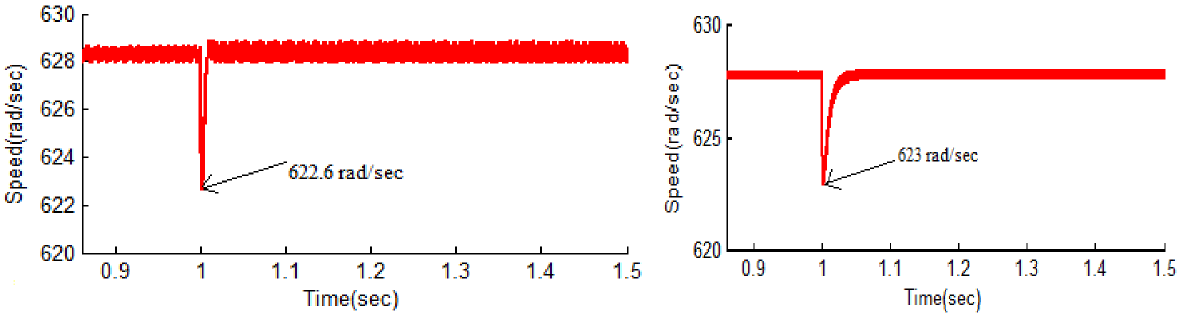


Figure 15 Speed response when load torque increases

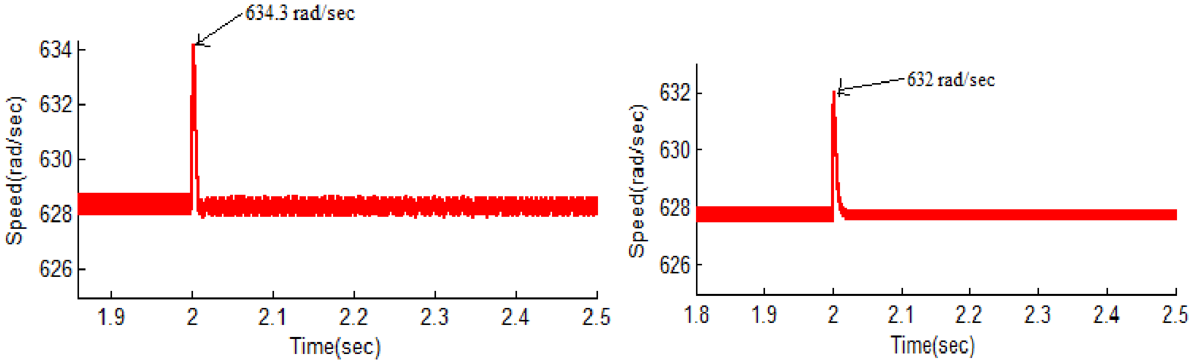


Figure 16 Speed response when load torque decreases

As shown in Fig. 14,15 and16 fuzzy controller also has a smooth recovery when load torque is applied. The advantages of fuzzy is there is a reduction in computational time and produces lower errors in speed drop than PI. In speed reference change there is a slight overshoot in PI as compared to fuzzy. By proper design a fuzzy logic controllers is much better then PI controllers for the speed control of dc motor drives. In speed reference change there is a slight overshoot in PI as compared to fuzzy.

V. Controller Implementation Using Microcontroller

A virtual BLDC motor model was developed using a microcontroller based model in which Euler method is used to solve the differential equations to give the motor characteristics. The virtual motor mimics behavior of the real motor in its characteristics. The hall sensor output from the virtual motor is given as feedback to the controller module, which gives appropriate gating signals to the inverter switches. The virtual motor takes the three terminal voltages from the inverter as the input and load torque as another input to the virtual motor. The various modules of the virtual motor generate the phase currents, position theta as the output. The sub-modules of the virtual motor generate the back emf and hall sensor signals from the rotor position. The output of virtual motor is digital. The simplified representation of the virtual motor is as given in Fig.17.

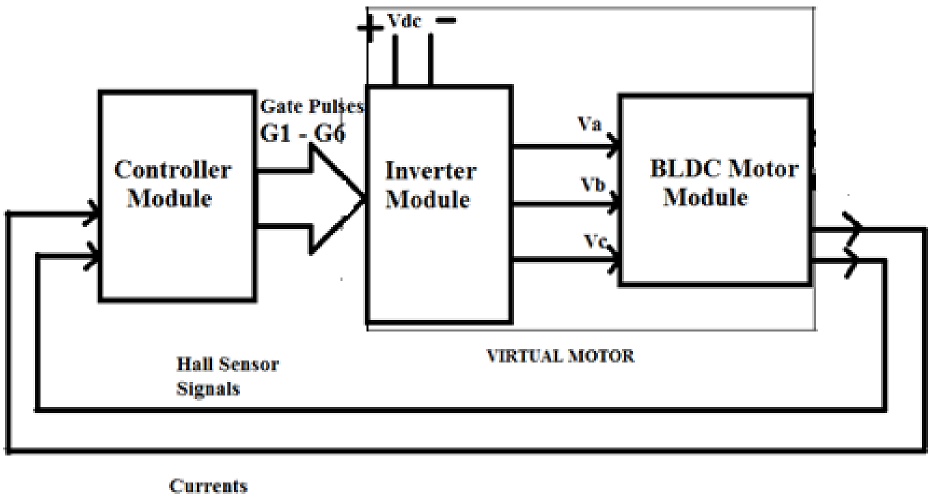
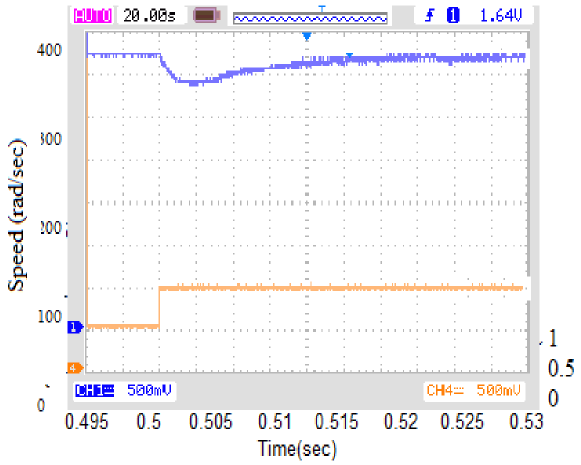


Figure 17 Virtual BLDC motor with controller module

VI. Validation of Results Using Virtual Motor

6.1.Simulation results for change in load torque

The controller model was designed and run for the condition where load torque increases from 0.475Nm to 0.95Nm and back to 0.475Nm. Speed refernce was kept constant at 314.16rad/sec.The following Fig. 18,19,20,21,22,23, 24 and 25.shows the output that is obtained in hardware and it is compared with the software output to the right.



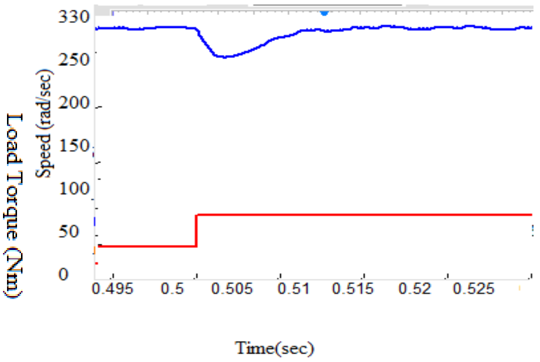
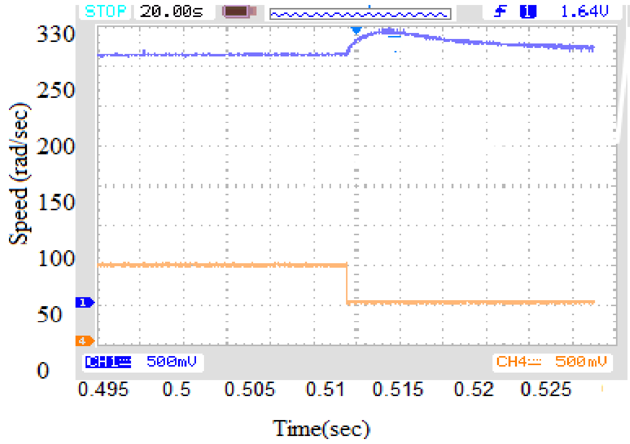


Figure 18 Virtual motor speeds when torque increases Figure 19 MATLAB speed when load torque increases



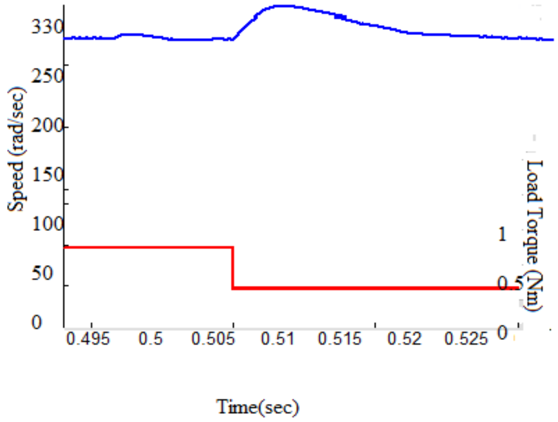
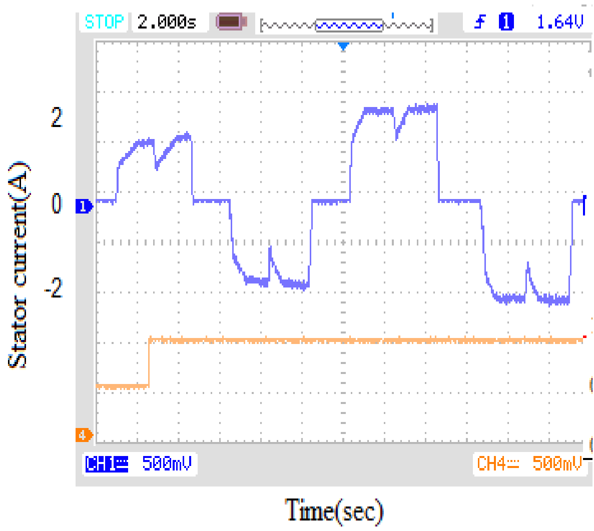


Figure 20 Virtual motor speed when torque deccreases Figure 21 MATLAB speed when load torque deccreases



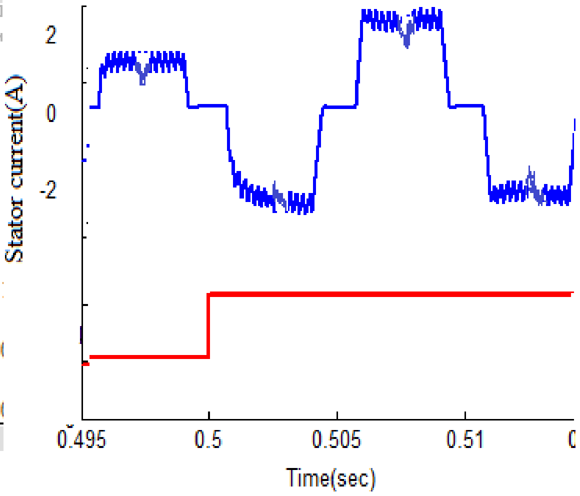
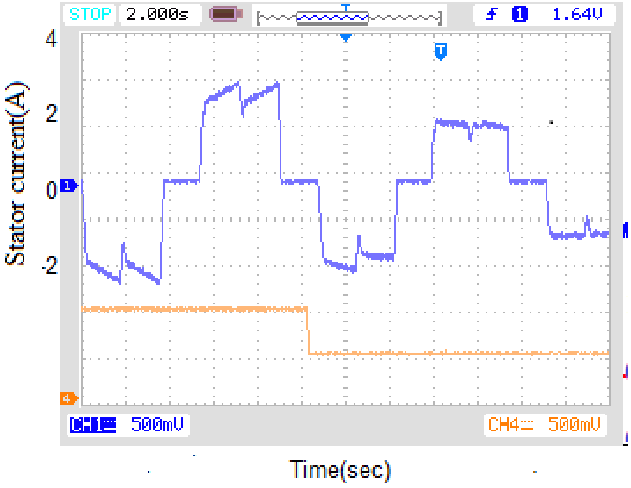


Figure 22 Virtual motor current when torque increases Figure 23 MATLAB current when load torque increases



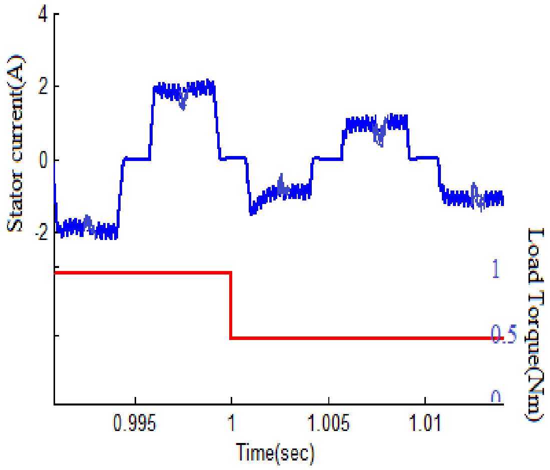
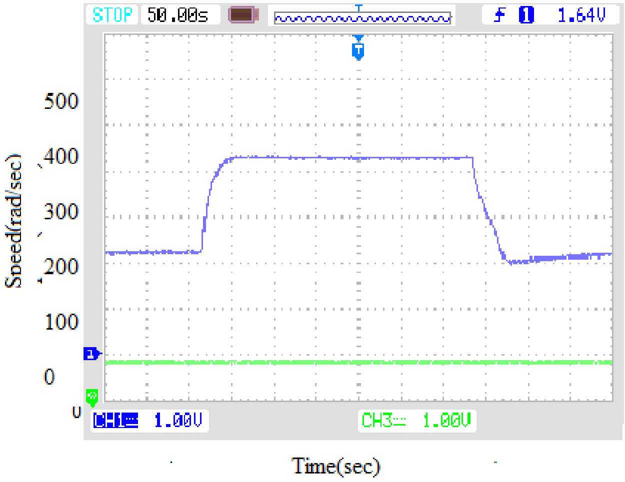


Figure 24 Virtual motor current when torque decreases Figure 25 MATLAB current when load torque increases

Results for change in refernce speed

The speed reference is changed from 209.44 rad/sec to 418.88 rad/sec and load torque is kept constant at 0.95 Nm. The speed graph follows the speed refernce and we obtain the following speed and current graphs as shown in Fig. 26, 27, 28 and 29.



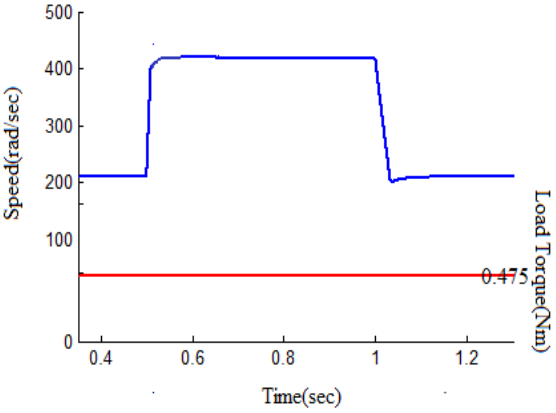
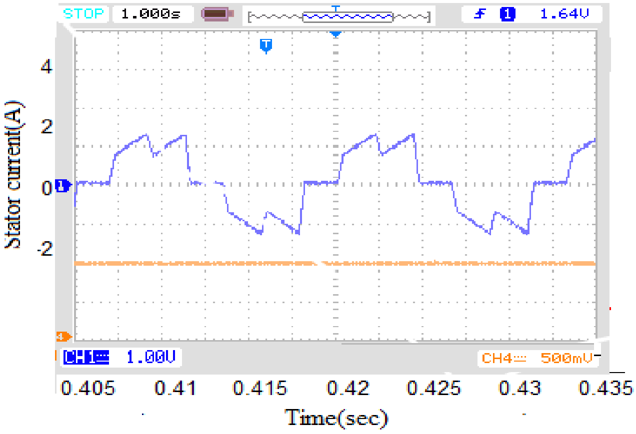


Figure 26 Virtual motor speed when speed reference changes Figure 27 MATLAB speed when speed reference changes



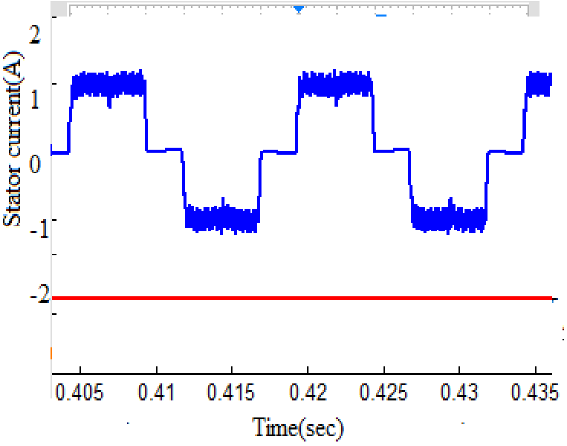


Figure 28 Virtual motor current when torque is constant Figure 29 MATLAB current when torque is constant

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VII. Conclusion

In this paper, the simulation of the drive is performed first with PI controller and then with fuzzy logic controller using Matlab/Simulink. The speed control is achieved at various load torque conditions with constant speed reference and at constant load with varying speed references. From the speed curve, it is seen that there is a peak overshoot in the case of PI controller but in fuzzy control, it is smooth. The fuzzy controller responds faster and smoother to reference speed changes compared to the PI controller. Mamdani fuzzy model proved to be more flexible, while developing a speed controller for constant speed reference with changing load torque, whereas, Sugeno fuzzy model proved to provide more accuracy for changing speed reference with constant load torque conditions The microcontroller based PI controller implementation is successfully tested with virtual motor.

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