Speed Torque characteristics of Brushless DC motor in either direction on load using ARM controller

M.V.Ramesh[1], J.Amarnath[2], S.Kamakshaiah[3], B.Jawaharlal[4], Gorantla.S.Rao[5]

1. Department of EEE, P.V.P Siddhartha Institute of Technology, Vijayawada, A.P, India.

2. Department of EEE, J N T U H College of Engineering, Hyderabad, A.P., India.

3. Department of EEE, Vignan Institute of Technology and Science, Hyderabad, India.

4. Scientist, DRDO-RCI, Hyderabad.

5. Department of EEE, Vignan University, Vadlamudi, India.

vrmaddukuri@gmail.com

Abstract

This paper presents the speed torque characteristics of BLDC motor on load in forward and reverse direction. The Hall sensors of the BLDC motor is bestowed as the input to the ARM controller. The PWMs are produced depending upon the input of the controller. In order to convert DC to three phase AC, three phase bridge inverter with MOSFET as switches is used. The generated PWMs are inputted to the gate of the MOSFETs in the inverter. The output of the inverter is the energization sequence of BLDC motor and only two phases energizes at once. Dynamometer is used for encumbering the motor. The results are acquired for variable load torque and Speed torque characteristics are observed.

Keywords: BLDC motor, PWM, MOSFET and dynamometer.

1. Introduction

Since 1980's new prototype concept of permanent magnet brushless motors has been built. The Permanent magnet brushless motors are categorized into two kinds depending upon the back EMF waveform, Brushless AC (BLAC) and Brushless DC (BLDC) motors [2]. BLDC motors have trapezoidal back EMF and quasi-rectangular current waveform. BLDC motors are quickly becoming famous in industries like Appliances, HVAC 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 [1].In the event of replacing the function of alternators and brushes, the BLDC motor requires an inverter and a position sensor that exposes rotor position for appropriate alternation of current. The rotation of the BLDC motor is built on the feedback of rotor position that is gained from the hall sensors. BLDC motor generally utilizes three hall sensors for deciding the commutation sequence. In BLDC motor the power losses are in the stator where heat can be easily shifted through the frame or cooling systems are utilized in massive machines. BLDC motors have many benefits over DC motors and induction motors. Some of the benefits are better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges [2].Till now, over 80% of the controllers are PI (Proportional and integral) controllers because they are facile and easy to comprehend [3].

The speed controllers are the conventional PI controllers and current controllers are the P controllers to

achieve high performance drive. Fuzzy logic can be considered as a mathematical theory combining multi-valued logic, probability theory, and artificial intelligence to simulate the human approach in the solution of various problems by using an approximate reasoning to relate different data sets and to make decisions. It has been reported that fuzzy controllers are more robust to plant parameter changes than classical PI or controllers and have better noise rejection capabilities. In this paper, hardware implementation of the BLDC motor is done by using ARM controller. We propose the Speed Torque characteristics of the BLDC motor drive rotating not only in forward but also in reverse direction. We used dynamometer with hysteresis brake to load the motor. The torque and speed of the BLDC motor is measured in dynamometer and basing on the readings Speed Torque characteristics ware drawn. The paper is organized as follows: Section II explains about construction and operating principle of BLDC motor, Section III elaborates the modelling of BLDC motor, Section IV presents the hardware implementation of BLDC motor. The hardware results are presented in detail in Section V and Section VI concludes the paper.

2.   Construction and Operating Principle

BLDC motors are a kind of synchronous motor. This indicates the magnetic field produced by the stator and the magnetic field produced by the rotor twirls at the same frequency. BLDC motors do not experience the "slip" that is normally observed in induction motors. BLDC motor is built with a permanent magnet rotor and wire wound stator poles.

1.1. Stator

The stator of a BLDC motor as shown in Fig.1 comprises of stacked steel laminations with windings kept in the slots that are axially cut along the inner periphery as shown in Figure 1. Most BLDC motors have three stator windings linked in star fashion. Each of these windings is assembled with various coils interconnected to derive a winding. One or more coils are kept in the slots and they are interconnected to form a winding. Each of these windings is distributed over the stator periphery to form an even numbers of poles.

1.2. Rotor

The rotor is formed from permanent magnet and can alter from two to eight pole pairs with alternate North (N) and South (S) poles. The suitable magnetic material is selected to form the motor depending upon the required field density in the rotor. Ferrite magnets are used to make permanent magnets. Now a day, rare earth alloy magnets are gaining popularity.

Fig. 1 Stator of a BLDC motor

1.3. Hall Sensors

The commutation of a BLDC motor as shown in Fig.2 is in check electronically. In order to rotate the BLDC motor, the stator windings ought to be energized in an order. It is essential to understand the rotor position in order to know which winding will be energized following the energizing sequence. Rotor position is perceived using Hall effect sensors embedded into the stator on the non-driving end of the motor as shown in fig. . Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, suggesting the N or S pole is passing near the sensors. The exact order of commutation can be estimated, depending upon the combination of these three Hall sensor signals.
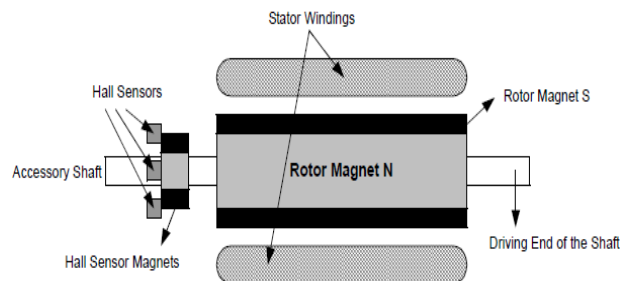
Fig. 2 Rotor and Hall sensors of BLDC motor

1.4. Theory of operation

Each commutation sequence has one of the windings energized to positive power, the second winding is negative and the third is in a non-energized condition. Torque is engendered because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque takes place when these two fields are at 90° to each other and goes down as the fields move together. In order to place the motor running, the magnetic field generated by the windings should shift position, as the rotor moves to catch up with the stator field [9].

1.5. Commutation Sequence

The commutation sequence, for every 60 electrical degrees of rotation, one of the Hall sensors changes the state. It takes six steps to finish an electrical cycle. In Synchronous, with every 60 electrical degrees, the phase current switching ought to be renovated. However, one electrical cycle may not agree to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is dictated by the rotor pole pairs. One electrical cycle is completed for each rotor pole pairs. Hence, the number of electrical cycles equals the rotor pole pairs. A three phase bridge inverter is used to balance the BLDC motor. There are six switches and these switches should be switched depending upon Hall sensor inputs. The Pulse width modulation techniques are used to switch ON or OFF the switches. In order to vary the speed, these signals should be Pulse Width Modulated (PWM) at a much higher frequency than the motor frequency. The PWM frequency should be at least 10 times that of the maximum frequency of the motor. When the duty cycle of PWM is differed within the sequences, the average voltage supplied to the stator reduces, thus lowering the speed. Another benefit of having PWM is that, if the DC bus voltage is much greater than the motor rated voltage, the motor can be controlled by limiting the percentage of PWM duty cycle corresponding to that of the motor rated voltage. This adds plasticity to the controller to assemblage motors with various rated voltages and matches the average voltage output by the controller, to the motor rated voltage, by controlling the PWM duty cycle. The speed and torque of the motor hinge upon the strength of the magnetic field generated by the energized windings of the motor that depend on the current through them. Hence the adjustment of the rotor voltage (and current) will change the motor speed.

2.   Modelling of BLDC Motor

The flux distribution in BLDC motor is trapezoidal and hence the d–q rotor reference frames model is not suitable. It is shrewd to derive a model of the PMBLDC motor in phase variables when if is given the non-sinusoidal flux distribution. The derivation of this model is depends on the postulations that the induced currents in the rotor due to stator harmonic fields, iron and stray losses are neglected. The motor is taken to have three phases even though for any number of phases the derivation procedure is true to life. Modeling of the BLDC motor is done applying classical modeling equations and therefore the motor model is highly adaptable. These equations are illustrated depending upon the dynamic equivalent circuit of BLDC motor. The assumptions made for modelling and simulation purpose are the common star connection of stator windings, three phase balanced system and uniform air gap. The mutual inductance between the stator phase windings are uncountable when compared to the self-inductance and so neglected in designing the model [3].

Dynamic model equation of motion of the motor is described in the form of equations (1) to (9).

$$W_m = (T_e - T_l) / J_s + B \qquad (1)$$

T_e – electromagnetic torque, T_l– load torque, J – moment of inertia, B – friction constant

Rotor displacement can be found out as,

$$\Theta_r = (P/2) W_m /s \qquad (2)$$

whereP – Number of poles

Back EMF will be of the form,

IISTE

$E_{as} = k_b f_{as}(\Theta_r)W_m$ (3) $E_{bs} = k_b f_{bs}(\Theta_r)W_m$ (4) $E_{cs} = k_b f_{cs}(\Theta_r)W_m$ (5)

where K_b -back EMF constant

Stator phase currents are estimated as,

$$i_a = (V_{as} - E_{as}) / (R + Ls) \quad (6) \quad i_b = (V_{bs} - E_{bs}) / (R + Ls) \quad (7) \quad i_c = (V_{cs} - E_{cs}) / (R + Ls) \quad (8)$$

where R – resistance per phase, L – inductance per phase

Electromagnetic torque developed,

$$T_e = (E_{as}i_{as} + E_{bs}i_{bs} + E_{cs}i_{cs}) / W_m \qquad (9)$$

3.   HARDWARE CONFIGURATION
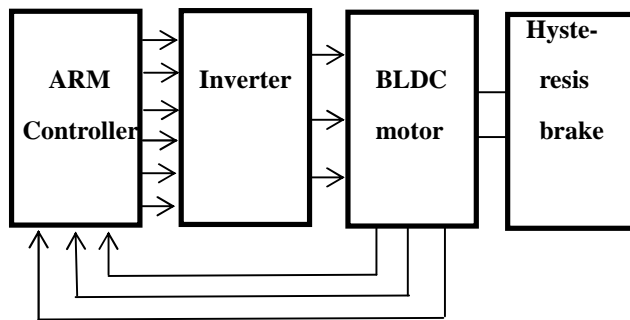
Fig. 4: Hardware configuration of BLDC motor

The hardware configuration of BLDC motor with loading arrangement is shown in Fig.4. The block diagram comprises ARM controller, three phase bridge Inverter, BLDC motor and hysteresis brake. The hall sensor output of BLDC motor is provided as the input to ARM controller and the PWMs are generated which are provided as the input to inverter. The inverter converts DC to three phase AC and the AC supply is given to the BLDC motor. The load is applied to the BLDC motor by coupling hysteresis brake with the BLDC motor. When the load on the BLDC motor increases, the speed decreases.

3.1. INVERTER

The circuit of three phase bridge inverter is shown in fig. 5. A three phase inverter is applied to transfer DC to three phase AC. Here six MOSFETs are used as the switches. P-channel MOSFET is linked with the upper arm and N-channel MOSFET is linked with the lower arm of the inverter. The symbol and ratings of N-channel MOSFET is shown in fig. 6. Among them, two of the six MOSFETs are energized at once. At this situation, one switch from the upper arm and one from the lower arm are turned on. Therefore, two phases will be energized. The current will flow into the motor from upper arm turn on switch and return from bottom arm turn on switch.
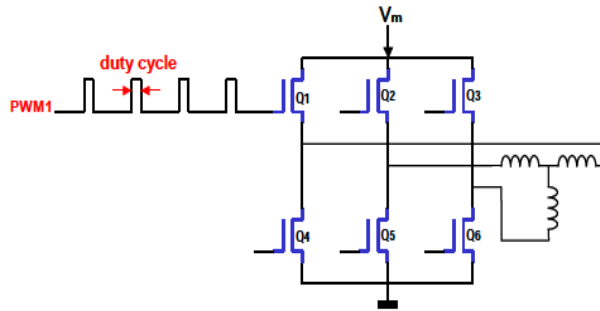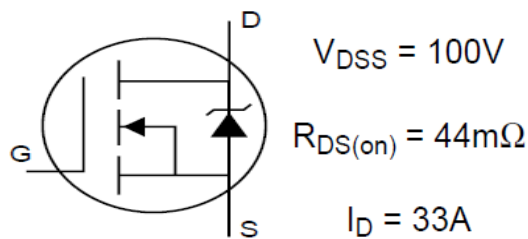
Fig. 5: Three phase Inverter circuit

Fig. 6: Symbol and Ratings of MOSFET

HPCL 3120 MOSFET drivers are used to drive the switches. MOSFET driver is the opto-coupler for cutting off the microcontroller from inverter circuit. The HCPL-3120 comprises a GaAsP LED optically coupled to a built-in circuit with a power output stage. This opto-coupler is ideally fit for driving power IGBTs and MOSFETs applied in motor control inverter applications. The high operating voltage range of the output stage furnishes the drive voltages necessary by gate controlled devices. The voltage and current supplied by this opto-coupler makes it ideally fit for directly driving IGBTs with ratings up to 1200V/100A.PWM is given as the input to the driver of the concerned switches. The output of the three phase inverter is the trapezoidal waveform because one from the upper arm and one from the lower arm will conduct. The functional diagram of HPCL 3120 is shown in fig. 7.
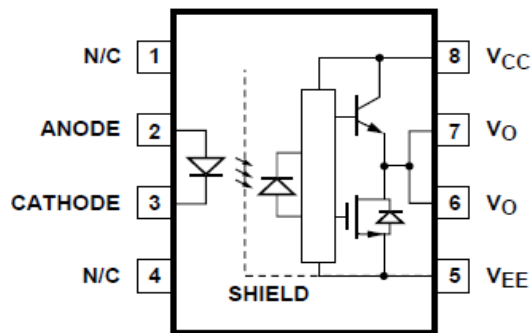
Fig. 7: Functional diagram of HPCL 3120
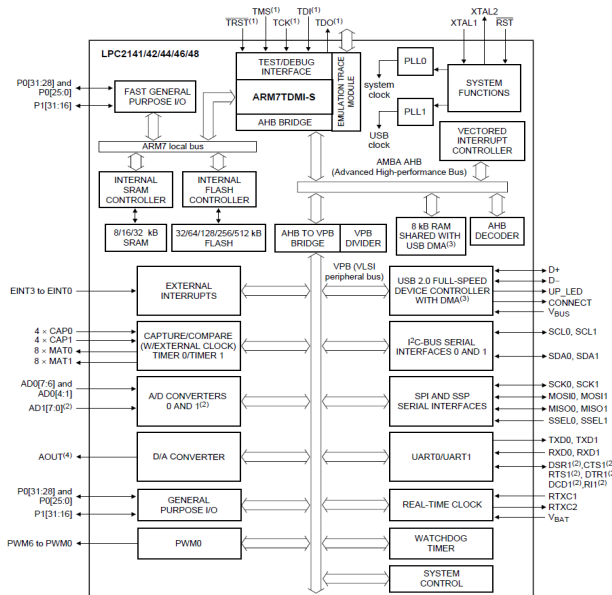
Fig. 8: Architecture of ARM controller

3.2. CONTROLLER

ARM 2148 controller is 16/32-bit, 8 to 40 KB of on-chip static RAM and 32 to 512 KB of on-chip flash program memory, 128 bit wide interface/accelerator enables high speed 60 MHz operation, USB 2.0 Full Speed compliant Device Controller, 8KB of on-chip RAM accessible to USB by DMA, two 10-bit A/D converters, two 32-bit timers/external event counters PWM unit and watchdog, low power real-time clock with independent power and dedicated 32 kHz clock input, On-chip integrated oscillator operates with an external crystal in range from 1 MHz to 30 MHz and with an external oscillator up to 50 MHz, Processor wake-up from Power-down, Single power supply chip with Power-On Reset (POR) and BOD circuits: CPU operating voltage range of 3.0 V to 3.6 V (3.3 V ± 10 %) with 5 V tolerant I/O pads. The architecture of ARM 2148 is shown in fig. 8.

3.3. DYNAMOMETER

The loading structure of the BLDC motor is constructed by applying dynamometer. It comprises of hysteresis brake with torque and speed controller. The BLDC motor is burdened by applying the brakes. The torque, speed and power can be measured.   TM 302 In-line torque transducer is used to measure the torque and power. The features of torque transducer are Integrated Torque and Speed Conditioning 0.1 Nm to 20 Nm, Accuracy< 0.1%, Overload Capacity of 200%, Overload Limit of 400%, Non-Contact, No Electronic Components in Rotation, High Electrical Noise Immunity, Single DC Power Supply of 20Vdc to 32Vdc, Immediate Speed Detection, Adjustable Torque Signal Frequency Limitation, Built-in Test Function, Stainless Steel Shaft, EMC Susceptibility Conforms to European Standards. The torque transducer diagram is shown in fig.9.

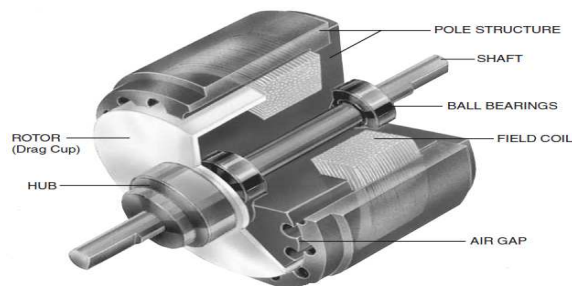Fig. 9: Diagram of Torque transducer.

Fig. 10: Model diagram of Hysteresis brake

AHB-1 model Series Compressed-air-cooled Hysteresis Brake is used to employ brakes on BLDC motor. The features of hysteresis brake are ideal for low-torque/high speed applications with phenomenal power ratings, Torque of 1 Nm to 24 Nm, Speed up to 25,000 rpm, Power up to 5300 W, Compressed-air cooling offers excellent heat dissipation, Allowable input air pressure of up 95 PSI eliminates the need for a regulator and provides precise torque control independent of shaft speed. The model diagram of hysteresis brake is shown in fig. 10.

4. Simulation and Experimental Results
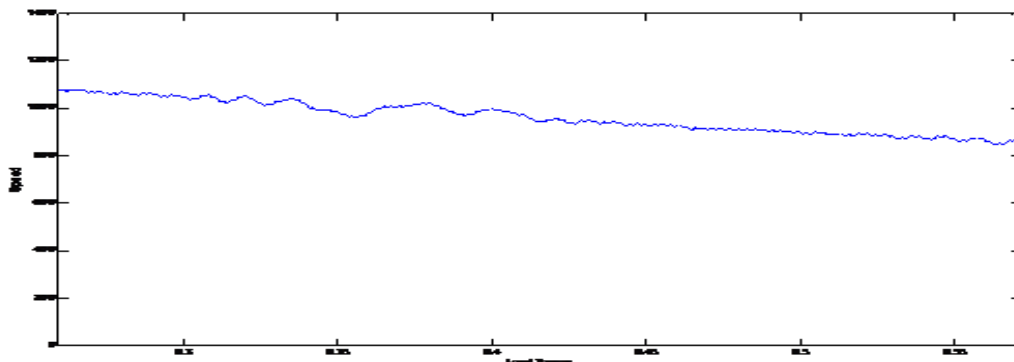
Fig. 11: Simulated Speed torque characteristics of BLDC motor in forward direction.

The simulation was done in MATLAB/Simulink and the Speed Torque characteristics in both forward as

well as reverse direction were drawn as shown in the figure. The load torque is continuously varying and the variation of the Speed is observed in both forward and reverse direction. The Speed-Torque characteristic in the forward direction is shown in fig. 11. The Speed-Torque characteristic in the forward direction is shown in fig. 12.
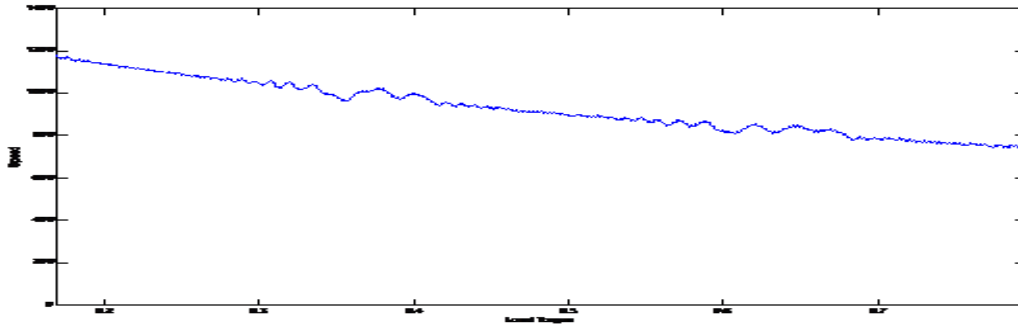

Fig. 12: Simulated Speed torque characteristics of BLDC motor in reverse direction

Fig. 13: Hardware Implementation

The Experiment is done on BLDC motor by connecting inverter with ARM controller. Dynamometer is linked with the BLDC motor and hysteresis brake is applied to the BLDC motor. When the brake is applied, the load torque increases and therefore the speed of the motor decreases. The BLDC motor is rotated in both forward as well as reverse direction. The reading of Speed, torque and power is taken from the dynamometer. The Speed-Torque characteristics of the BLDC motor are drawn individually for forward and reverse directions. Fig.11 shows the Speed-Torque characteristics of the BLDC motor in forward direction. Fig.12 shows the Speed-Torque characteristics of the BLDC motor in reverse direction. The Speed-Torque characteristics of the BLDC motor are compared when the BLDC motor is rotated in both forward as well as reverse direction. Fig.13 shows comparison of the Speed-Torque characteristics of the BLDC motor in forward as well as reverse direction.
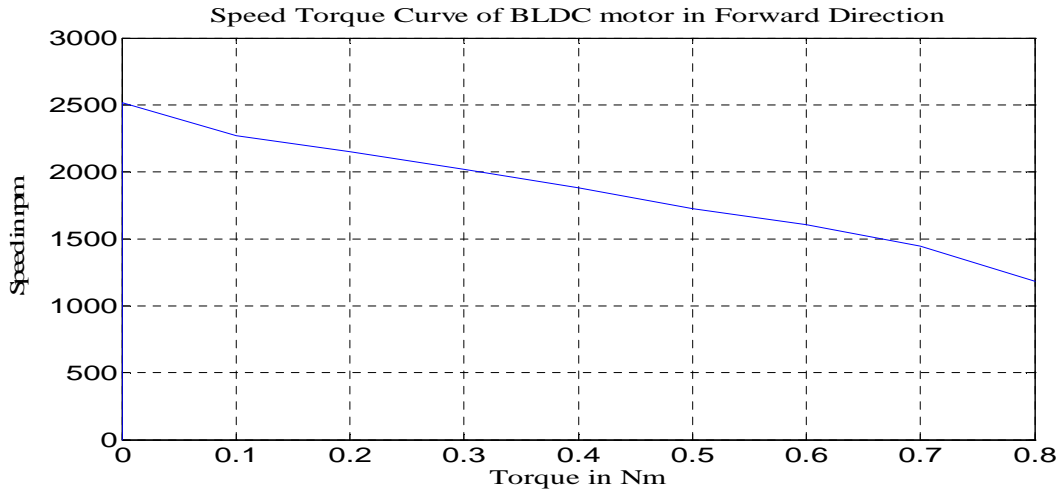
Fig. 14: Speed torque characteristics of BLDC motor in forward direction.
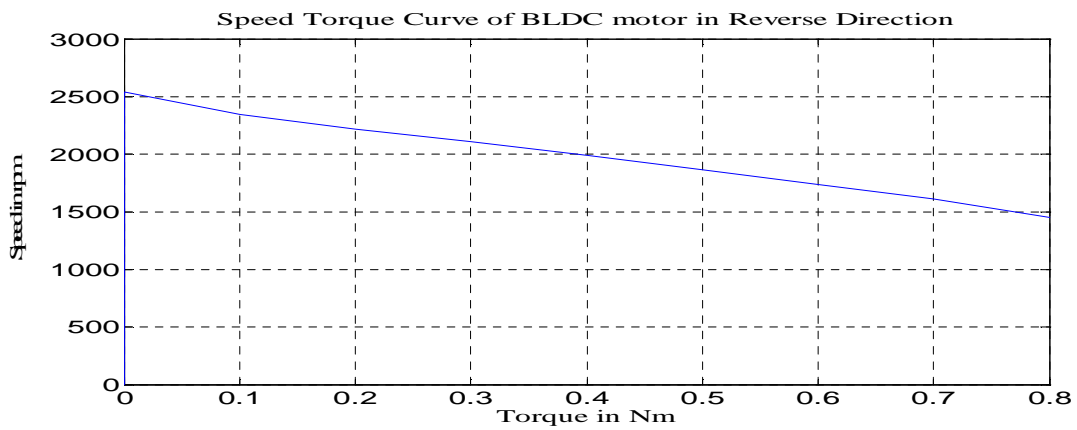

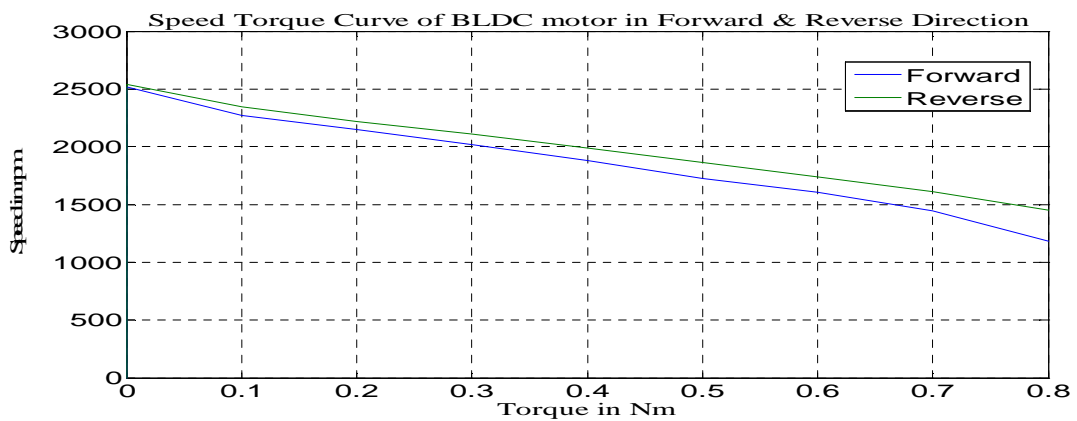Fig. 15: Speed torque characteristics of BLDC motor in reverse direction.

Fig. 13: Speed-Torque characteristics of BLDC motor in both forward as well as reverse direction.

From fig. 13 we can observe that the Speed Torque characteristics of BLDC motor has some difference in

dropping characteristics when it rotates in forward and reverse direction. The simulated and experimental results for the Speed-Torque characteristics of BLDC motor drive in forward and reverse direction are presented. The Specifications of Motor are shown in Table.1

5. Conclusions

In this paper, the BLDC motor is restrained by utilizing ARM controller. The MOSFETs are used in three phase bridge inverter for converting DC to three phase AC. HPCL 3120 driver is used to drive the MOSFETs and also to isolate the inverter circuit from ARM controller. The speed of the BLDC motor can be differed by changing the turn on time of the PWM. The hall sensor output of the BLDC motor is inputted to the ARM controller. The loading arrangement of the BLDC motor is given by dynamometer. The load torque of the BLDC motor is varied by applying the torque sensor. The speed, torque and power of the BLDC motor are measured and the Speed-Torque characteristics are drawn when the motor is rotating not only in forward but also in reverse direction. The simulated values of the BLDC motor can be compared with the experimental results.

Table 1: Motor ratings

Specifications	Units
No. of poles	4
Moment of inertia, J	0.00022 Kg-m^2
Flux density, B	0
Stator resistance, R	0.7
Stator Inductance, L	5.21mH
Terminal Voltage, V	24
Motor constant	0.10476

References

P.Pillay and R.krrishnan. "Modelling , simulation and analysis of a Permanent magnet brushless DC motor drive", *IEEE Transaction on Industrial Applicantions*, Vol26, pp124-129,2002.

"AN885 - Brushless DC (BLDC) Motor Fundamentals" 2003 Microchip Technology Inc.

IRF540N Advanced HEXFET® Power MOSFETs from International Rectifier.

AHB-1 Series Compressed-air-cooled Hysteresis brake datasheet from Magtrol.

TM 301-308 In-line Torque Transducer datasheet from Magtrol.

HPCL-3120 2Amps Output Current IGBT/MOSFET Gate driver Optocoupler datasheet from Hewlett Packard.

2N2222 NPN switching Transistor datasheet from Discrete Semiconductors.

UM10139, LPC214x User Manual from Philips Semiconductors.

"AN10661, Brushless DC motor control using the LPC 2141", an application note from Philips Semiconductors.

"AN885 - Brushless DC (BLDC) Motor Fundamentals", 2003 Microchip Technology Inc.

M.V.Ramesh received the B.Tech degree in Electrical and Electronics Engineering from Nagarjuna University in the year 1998 and M.S (Electrical Engineering) from German university in the year 2002. Since June 2003 working as an Assistant Professor at P.V.P.S.I.T Engineering College, Vijayawada. His research interests include Power electronics and drives, Power system automation, Hybrid Vehicle Design and Reactive power compensation. He published several papers at the national and international conferences.

J. Amarnath graduated from Osmania University in the year 1982, M.E from Andhra University in the year 1984 and Ph.D from J.N.T. University, Hyderabad in the year 2001. He is presently Professor in the Department of Electrical and Electronics Engineering, JNTU College of Engineering, Hyderabad, India. He presented more than 60 research papers in various national and international conferences and journals. His research areas include Gas Insulated Substations, High Voltage Engineering, Power Systems and Electrical Drives.

S. Kamakshaiah graduated from Osmania University. He obtained M.E (HV) from IISc, Bangalore and Ph.D also from IISc, Bangalore He is former professor & Head of Electrical & Electronics Engineering and chairman of Electrical science J.N.T.University, Hyderabad. He is presently Professor in the Department of Electrical and Electronics Engineering, Vignan college of Engineering, Hyderabad, India. He presented many research papers in various national and international conferences and journals. His research areas include Electrical Machines, High Voltage Engineering, Power Systems, and Electromagnetic Fields.

B.Jawaharlal received the B.Tech degree in Electrical and Electronics Engineering from Andhra University in the year 1998 and M.E from IISc Bangalore in the year 2000. From 2001-2007 worked as Scientist in DRDO/NSTL, Vishakapatnam and at present working as Scientist in DRDO/RCI, Hyderabad.