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Fuzzy Logic based Speed Control of BLDC Motor on Sensorless Technique for Space Applications

K. Neethu[1], M. Boopathi[2], Giriraj Mannayee[2*] and T. C. Kanish[2]

[1]Department of Mechatronics, Nehru College of Engineering and Research Centre, Pampadi, Thrissur - 680597, Kerala, India

[2]School of Mechanical Engineering (SMEC), VIT University, Vellore - 632014, Tamil Nadu, India; girirajmannayee@yahoo.com

Abstract

For space applications there is an increasing trend to move towards using Brushless Direct Current (BLDC) motors because of their high efficiency, silent operation, compact form, reliability, and low maintenance. Traditionally, BLDC motors are commutated in six-step pattern with commutation controlled by position sensors. BLDC motors do require rotor position information in order to select the appropriate commutation angle. To reduce cost and complexity of the drive system, sensorless drive is preferred. In this paper, circuits have been designed for sensorless control technique to be used in space application and carrying out its simulation in MATLAB using controller (FLC).The sensorless rotor position technique detects the zero crossing points of trapezoidal Back-EMF induced in the BLDC motor windings. Three phase Back-EMF Zero Crossing points are sensed while one of the three phase windings is not powered. The obtained information is processed in order to commutate the energized phase pair.

Keywords: BLDC Motor, Back EMF, Pulse Width Modulation (PWM), Zero Crossing Detection

1. Introduction

Today motor control systems are used by engineers for both digital and analog technologies to conquer past challenges including motor speed control, rotation direction, drift and motor fatigue. This motor control system has been sprouted in small and large scale applications along with ecofriendly electronics for reducing the energy consumption. So designers need motor which have better characteristics and performance which fits in to the above problem. This leads to the development of brushless direct current (BLDC) motors. BLDC motors are specifically used in areas where space, weight, reliability and energy consumption are critical factors. Example for such an area is space application. BLDC motors are the best type of motors for space applications than other type, because of their long life, high torque, high efficiency, and low heat dissipation. BLDC motors provide the lightest weight alternative for most applications. Space applications for BLDC motor are Thrust Vector Control (TVC) actuators, Fuel valve control actuators, solar array deployment, Control moment gyroscopes, High RPM applications, Light weight applications, Low thermal emission applications. Advantages of BLDC motor are High efficiency, reliability, less size and weight, easy speed control, low rate of maintenance, wide speed range and silent operation motor.

The BLDC motor uses electronic commutation to control the current through the windings. The BLDC motors use permanent magnets on the rotor and the stator is wound with electromagnetic coils. Sensing devices define the rotor position. The commutation logic and switching electronics convert the rotor position information to the correct excitation for the stator phases. Rotor position has to be sensed accurately for proper commutation. Sensing devices include hall-effect transducers, absolute encoders, optical encoders, and resolvers are used for detecting the rotor position. Sensored control has so many drawbacks. Sensor and their associated connectors results in increased system cost, reduced reliability, not practical

*Author for correspondence

to use in some environments, sensitive to temperature, sometimes mounting of sensors not possible. For these reasons Sensorless control is desirable for space application. In this project, circuits are designed for sensorless control technique to be used in space application and carrying out simulation in MATLAB. The sensorless rotor position technique detects the zero crossing points of Back-EMF induced in the motor windings. BLDC motor has trapezoidal shaped back EMF. Three phase Back-EMF Zero Crossing points are sensed while one of the three phase windings is not powered. The obtained information is processed in order to commutate the energized phase pair and to control the phase voltage using Pulse Width Modulation (PWM).

1.1 Problem Definition

Spacecraft mechanisms group of ISRO Satellite Centre (ISAC) at Bangalore is involved in design and development of solar panel and reflector deployment mechanisms. These mechanisms are traditionally driven with energy stored in springs. With considerable development and miniaturization observed in the motor control electronics, DC motors offer a very good alternative to spring based deployment. Brush DC motors are very good choice for deployment as the electronics involved is very simple. Brush wear is one of the major problems of Brush DC motor, with the vacuum operation, the problem is more serious. Stepper motors are good for pointing mechanisms applications. Due to the limitation on high speed these motor is less efficient. The drive electronics is quite simple for stepper motor as feedback device is not needed for their operation. Hence, the good choice for space appendage deployment is BLDC motor. However, the electronics involved is complex as the commutation needs to happen with the help of a feedback device. The BLDC motor with sensorless drive circuit is very good option as it reduces one more hardware in terms of feedback device hence increasing its reliability. This work was conducted with the purpose of developing a three phase Inverter and sensorless speed controlling in a BLDC-motor drive system for space application.

1.2 Objectives andMethodology

Objectives in this paper are

- Replacing the existing position sensor (Hall Effect sensor) used for space application with sensorless technique.
- Designing required circuits for sensorless technique.
- Modelling MATLAB/SIMULINK BLDC motor model
- Developing the fuzzy logic controller.

BLDC motor three phases with each phase having a conducting interval of 120 degrees and each phase has two steps per conducting interval. This is called six-step commutation. For example, the commutation phase sequence can be RG-RB-GB-GR-BR-BG as shown in Figure 1. Each conducting stage is one step and only two windings conduct current at any time, leaving the third winding floating. The un-energized winding can be used as a feedback control that forms the basis for the characteristics needed for control algorithms. In applications where precision is required, hall sensors or a tachometer are used to calculate the position, speed, and torque of the rotor. In applications where cost is the most important consideration, the sensorless technique—which is the calculation of the Back Electromotive Force (BEMF)—can be used to calculate position, speed, and torque.

Back electromotive force commonly known as Back-EMF (BEMF) is defined as the voltage that is created in

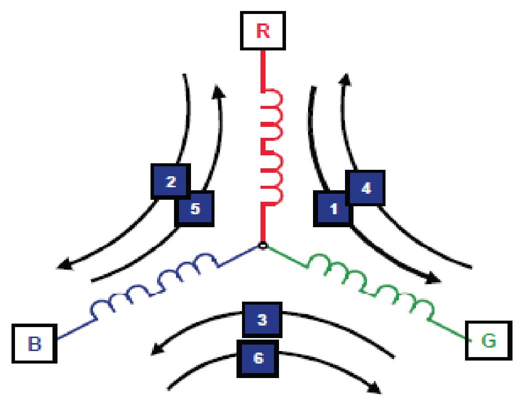

Figure 1. Three phases winding of BLDC motor.

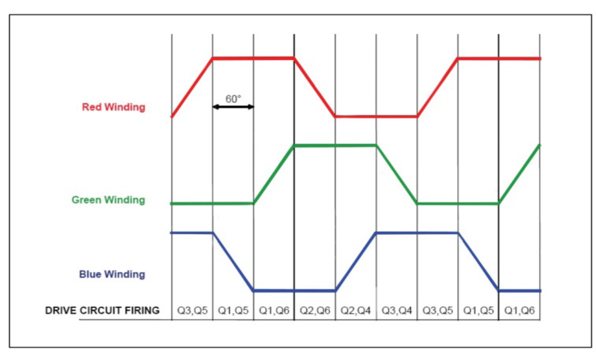

Figure 2. Trapezoidal BEMF of BLDC motor.

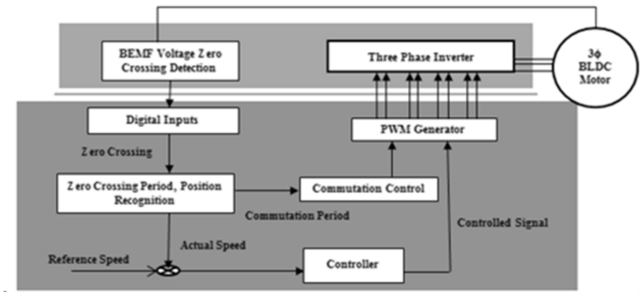

Figure 3. System concept of sensorless BLDC motor speed controller.

the stator winding by the permanent magnet. This occurs when the rotor of the motor is turning. For BLDC motor the back emf voltage obtained is in trapezoidal shape as shown in Figure 2. There are three vital back-EMF characteristics that can be utilized for control and feedback signals. The first is that the magnitude of the back-EMF be proportional to the speed of the motor. The second factor is that as speed increases, the slope of the back-EMF signal becomes greater. The third is that the back-EMF signal is symmetrical around the Crossing Event. Detecting the Crossing Event precisely is the key to implementing the back-EMF algorithm. The fundamental principle of this technique is to locate the Zero Crossing Points (ZCPs) of the phase back-EMFs. Based on this, sensorless operation using back-EMF ZCP detection is established. Accordingly, for all phases, the commutation is such that these ZCPs should be positioned mid-way in the silent periods. The concept as shown in the below Figure 3 is chosen. The sensorless rotor position technique developed detects the zero crossing points of Back-EMF induced in the BLDC motor windings. The phase Back-EMF Zero Crossing points are sensed while one of the three phase windings is not powered. The obtained information is processed in order to commutate the energized phase pair and control the phase voltage, using Pulse Width Modulation.

2. Modeling and Simulation

In this paper, a three phase connected trapezoidal back-EMF type BLDC motor is modelled. Trapezoidal back-EMF is referring that mutual inductance between stator and rotor has trapezoidal shape. The mathematical model of BLDC Motor is comprising into two parts: Electrical and Mechanical equations.

Electrical Equations

$$V_a = R * ia + L * \frac{dia}{dt} + e_a \tag{1}$$

$$V_b = R * i_b + L * \frac{dib}{dt} + e_b \tag{2}$$

$$V_c = R * i_c + L * \frac{dic}{dt} + e_c \tag{3}$$

where, V_a, V_b, V_c is the terminal voltage, R is the stator resistance, L is the stator inductance, ia, i_b, i_c is the stator phase current and e_a, e_b, e_c is the induced back emf in each phase.

In order to obtain the space model (1) and (2) are combined together with the fact that the sum of all phase currents will be zero, $i_a + i_b + i_c = 0$, which gives

$$i_a = 1/3LS\ [2V_{ab} + V_{bc} - 2e_a + e_b + e_c - 3*R\ i_a] \tag{4}$$

$$i_b = 1/3LS\ [-V_{ab} + V_{bc} + e_a - 2\ e_b + e_c - 3*R\ i_b] \tag{5}$$

This state space equation of phase current will be using in SIMULINK model of BLDC motor. The trapezoidal back-EMF in a 3-phase BLDC motor is related to a function of rotor position where each phase is 120 ° phase shifted and given by

$$e_a = K_b * w * f(\theta) \tag{6}$$

$$e_b = K_b * w * f(\theta + 2\Pi/3) \tag{7}$$

$$e_c = K_b * w * f(\theta - 2\Pi/3) \tag{8}$$

Where K_b is the motor back EMF constant (V/rad/sec), w is the rotor speed, θ is the electrical rotor angle and f is the trapezoidal shape reference function with respect to rotor position.

Mechanical Equations

$$T_e = B * w + J * \frac{dw}{dt} + T_l \tag{9}$$

where, Te is the total electromagnetic torque, B is the frictional coefficient (Nm/rad/sec, J is the moment of inertia (kgm²), T_l is the load at motor.

where, $T_e = (e_a\, i_a + e_b\, i_b + e_c\, i_c) / w \quad (10)$

Therefore, rotor speed is

$$w = 1/J\ S\ [T_e - B\ w - T_l] \tag{11}$$

2.1 Matlab / Simulink Models

Figure 4 shows the complete BLDC motor Simulink model and describing the blocks used for it.

The topology of a three-phase inverter consists of 3 legs; each leg includes 2 switches for executing the pulsation. Three phase inverter is developed using controlled voltage source block and universal bridge block as shown in Figure 5.The Controlled Voltage Source block converts the Simulink input signal into an equivalent voltage source. The Universal Bridge block implements a universal three-phase power inverter that consists of 3 arms and six power switches connected in a bridge configuration. The Universal Bridge block allows simulation of inverter using naturally commutated power electronic devices (diodes or thyristors) and forced-commutated devices (GTO, IGBT, MOSFET). From the terminals A and B. output signals V_{ab} and V_{bc} are obtained for further calculations.

Speed generator block is the mechanical part of BLDC motor. Developed this model for generating the actual speed (w) of the BLDC motor by using the mechanical and electrical equations. Rotor position angle can be analyzed by using the equation (22). Speed generator block is shown in Figure 6.

Current generator block is used to get the stator phase currents (i_a, i_b, i_c). It is developed using the state equations (8) and (9). It is shown in Figures 7 and 8.

EMF generator block is used to create BEMF of the BLDC motor is shown in Figure 9.

Rotor position angle (theta) conversion is done as shown in Figure 10 and also fuzzy logic controller block is implemented for making the necessary decision and for producing the required position alignment of each

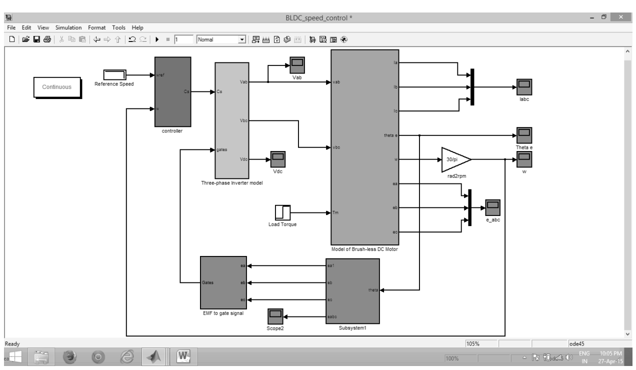

Figure 4. Simulink model of BLDC motor.

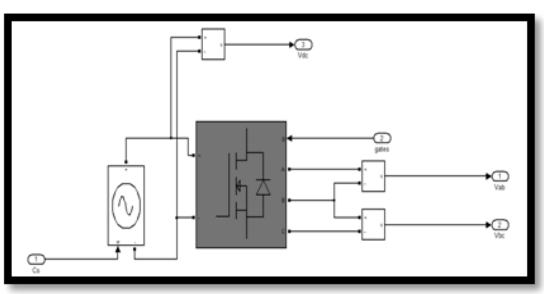

Figure 5. Three phase inverter model.

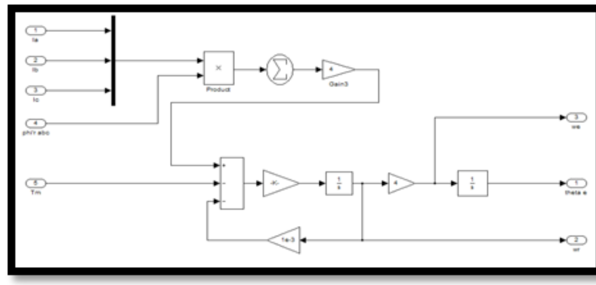

Figure 6. Speed generator model.

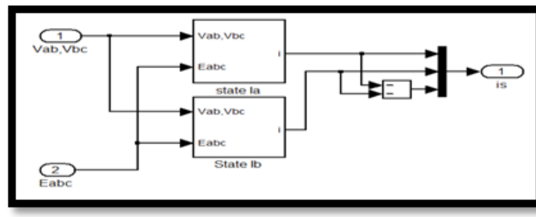

Figure 7. Current generator state equation model.

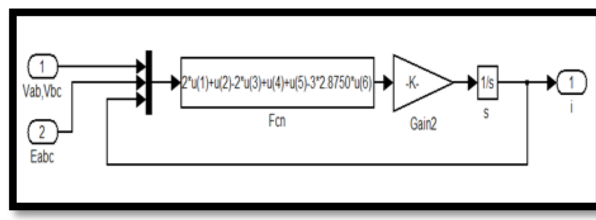

Figure 8. State equation model of phase current ia.

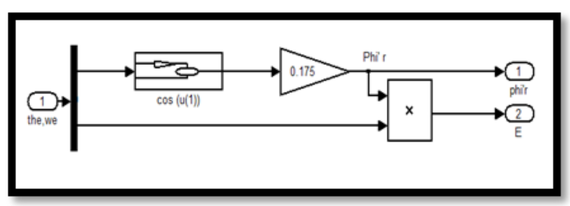

Figure 9. Emf generation block.

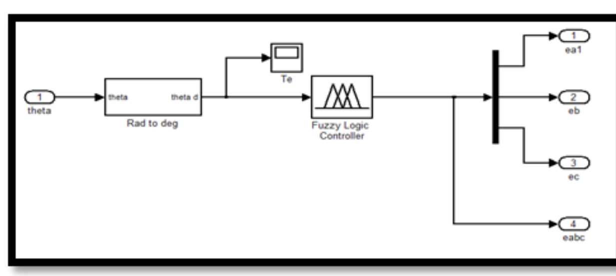

Figure 10. Subsystem – fuzzy logic controller.

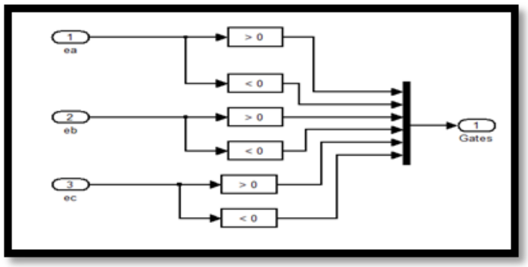

Figure 11. EMF to gate signal converter model.

phase. Signals from fuzzy logic controller subsystem are converted appropriately to gate signals using the zero comparators as shown in Figure 11. This in turn is applied to three phase inverter

2.2 Fuzzy Inference System

Fuzzy logic has rapidly become one of the most successful of today's technology for developing sophisticated control system. It is a rule based controller. The most important things in fuzzy logic control system designs are the process design of membership functions for input, outputs and the process design of fuzzy if-then rule knowledge base. Fuzzy Inference system for BLDC motor has one input (rotor position angle- theta) and three outputs (phase A, phase B, phase C) as shown in Figure 12 Input have six membership function which ranges from -180 to +180 (representing the angle) shown in Figure 13 and outputs have three membership functions -1, 0, +1 (representing ON and OFF) shown in Figure 14. Fuzzy rules are made according to the Table1.

2.3 Circuits Designed for Space Application

OrCAD is a software tool suite used primarily for electronic design automation. It is most widely used schematic design solutions for the creation and documentation of electrical circuits. The software is used mainly by electronic design engineers and electronic technicians to create electronic schematics and electronic prints for manufacturing printed circuit boards. Circuits required for the system has been developed using OrCAD PSpice software. The main circuit of the project back emf zero crossing detection circuit is shown in Figure 16. It is made of three LM139 comparators for each phase (A, B, C). Back EMFs are created by giving small delay between each phase. Back emf from each phase is compared with the reference voltage (0V) and when the reference voltage and input voltage is same, an output pulse is generated.

Table 1. Fuzzy rules table

Rotor Position Angle (theta)	Phase A	Phase B	Phase C
-180 → -120 (mf1)	-1 (mf1)	0 (mf2)	1 (mf3)
-120 → -60 (mf2)	0 (mf2)	-1 (mf1)	1 (mf3)
-60 → 0 (mf3)	1 (mf3)	-1 (mf1)	0 (mf2)
0 → 60 (mf4)	1 (mf3)	0 (mf2)	-1 (mf1)
60 → 120 (mf5)	0 (mf2)	1 (mf3)	-1 (mf1)
120 → 180 (mf6)	-1 (mf1)	1 (mf3)	0 (mf2)

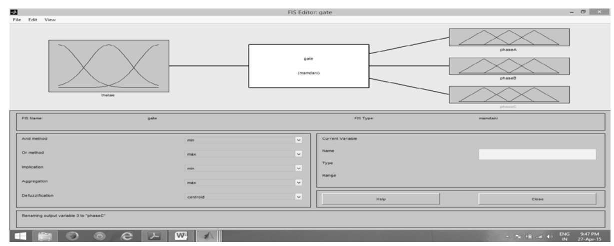

Figure 12. Fuzzy Inference system for BLDC motor speed controlling.

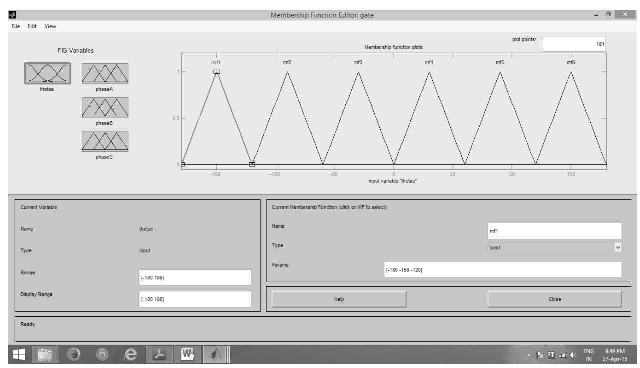

Figure 13. Input membership function (theta).

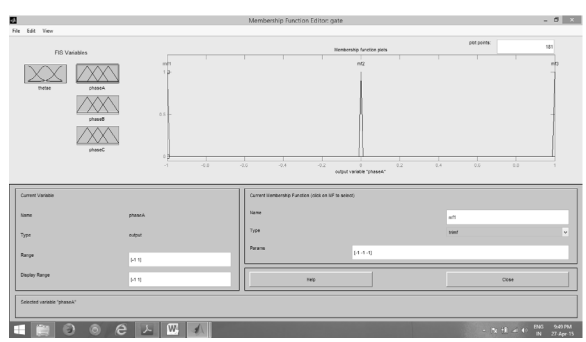

Figure 14. Output membership function.

Figure 15. FIS rule viewer.

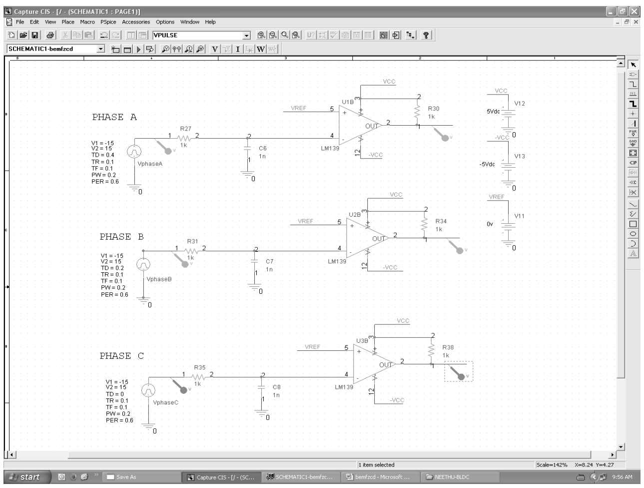

Figure 16. Back EMF-zero crossing detection circuit.

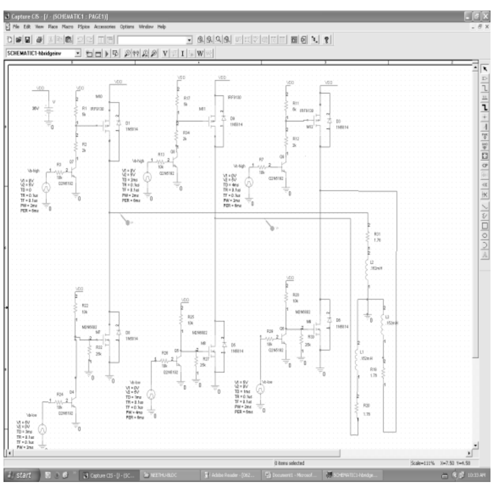

Figure 17. BLDC motor driver circuit.

In Figure 17 BLDC motor driving circuit which consists of six switches made of power MOSFETS and diodes are shown, which are used for triggering each phase in a consecutive sequence. The sequence of operation is AB, CB, CA, BA, BC, and AC, again it starts from AB. The speed of the BLDC motor is controlled by the width of the PWM signals. Using space qualified RTX2010 microcontroller PWM signals are generated. The circuits have to be developed with space grade hardware. For fine tuning the BEMF zerocrossing detection circuit, the back emf waveform of MAXON motor has been analyzed by making a experimetal setup. Then the back emf waveforms have been observed for different voltages using digital phosphor oscilloscope. Back emf that we got by running this motor contained high freequency noise components. So fine tuning of the RC filter which can be used for all voltage ranges was necessary at this point. Modified back emf zero crossing detection circuit is as shown in Figure 18.

In practical implementation this back emf zero crossing detection circuit using absoulte comparators may not work precisely. So as a solution to that problem we must include a schmitt trigger for this. Schmitt trigger is a comparator circuit with hysteresis, implemented by applying positive feedback to the noninverting input of a comparator or differential amplifier. It is an active circuit which converts an analog input signal to a digital output signal. In this the output retains its value until the input changes sufficiently to trigger a change. Back emf zero crossing detection circuit with schmitt trigger is shown in Figure 19. Upper Threshold Limit (UTL) is +0.5V and lower threshold limit (LTL) is -0.5V.

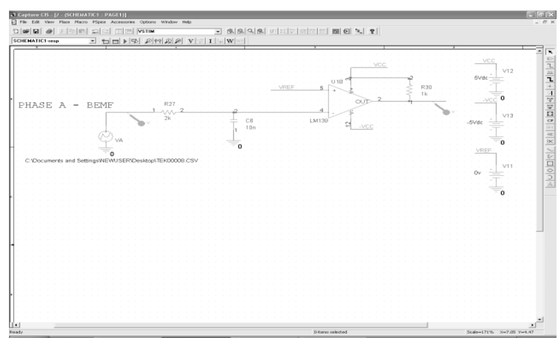

Figure 18. Modified BEMF ZCD circuit for real time input.

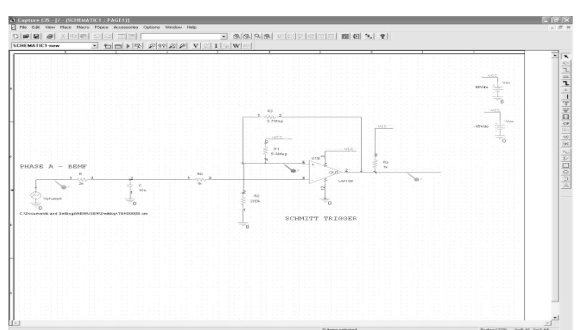

Figure 19. BEMF ZCD circuit with Schmitt trigger.

3. Simulation Results

The BLDC motor Simulink model has been simulated and the waveforms are provided below. BLDC motor reference speed was set as 2000 rpm and then reducing to 1000 rpm after a time period of 0.4 seconds and applying a load torque of 2Nm after 0.2 seconds from motor start. Waveform of trapezoidal shaped Back EMF (e_a, e_b, e_c) generated using EMF generator block and state equation is shown in Figure 20. After 0.4 seconds BEMF voltage reduces as speed reduces which states that BEMF is directly proportional to BLDC motor speed.

Actual motor speed plot in rpm is shown in Figure 21 and the speed reducing to 1000 rpm from 2000 rpm gradually and at 0.2 seconds there is a decrease in speed due to load torque and again settling.

Gate signal generated by comparing BEMF signals with zero is shown in Figure 22 Gate pulse width increased after 0.4 seconds , as the speed got reduced.

Circuits required for the system has been developed using OrCAD PSpice software. And the simulation results are shown below. The main circuit of the project is back emf zero crossing detection circuit. When the trapezoidal BEMF crosses the zero voltage, an output pulse is generated. Waveform of zero crossing detection of all three phases is shown in Figure 23. BLDC motor driving circuit which consists of six switches made of power MOSFETS and diodes needs six PWM signals for triggering each phase in a consecutive sequence. Waveform of those six PWM signals to three phase inverter is shown in Figure 24. The sequence of operation is AB, CB, CA, BA, BC, and AC, again it starts from AB.

Many voltage and current sources can be defined for our design. But sometimes real time measured data have to be used as a source for PSpice simulation. This can have achieved with the help of VPWL_FILE for voltage source. Back emf waveforms obtained using digital phosphor oscilloscope has to be ported as comma separated value (.csv) file. From the Figure 25 it can be seen that real time input back emf waveform has high frequency noise components, but these noises got filtered and required back emf zero crossing points are only detected by the circuit and giving accurate digital output.

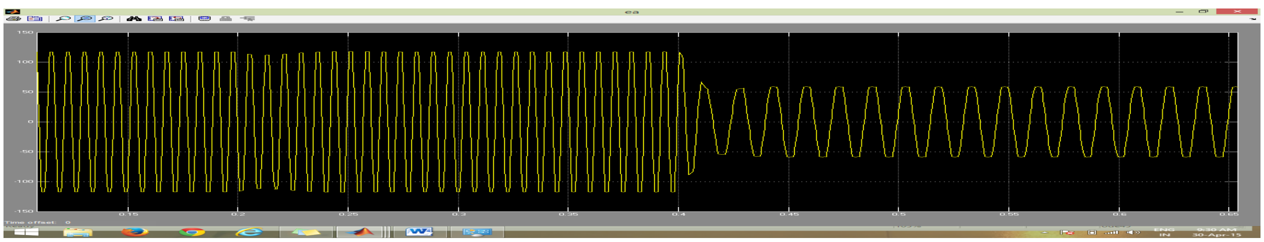

Figure 20. Waveform of BEMF.

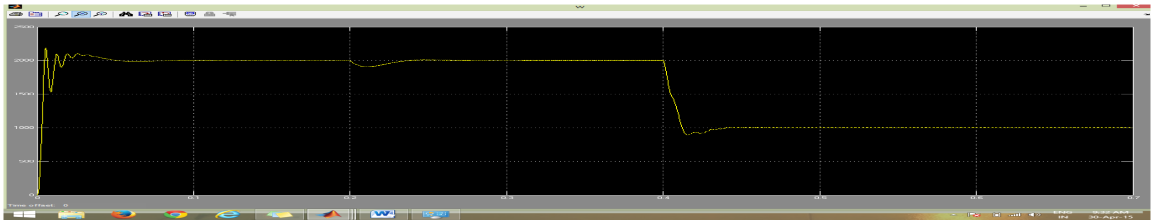

Figure 21. Actual motor speed plot in rpm.

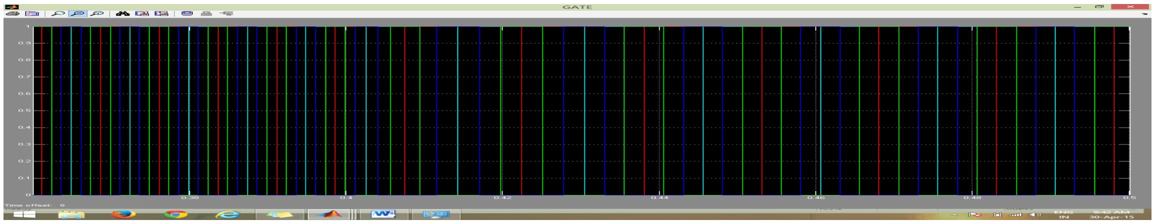

Figure 22. Plot for gate signals.

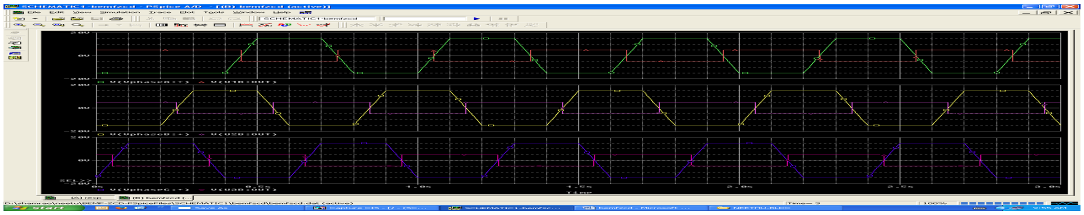

Figure 23. Waveforms of Zero Crossing Points for all three phases.

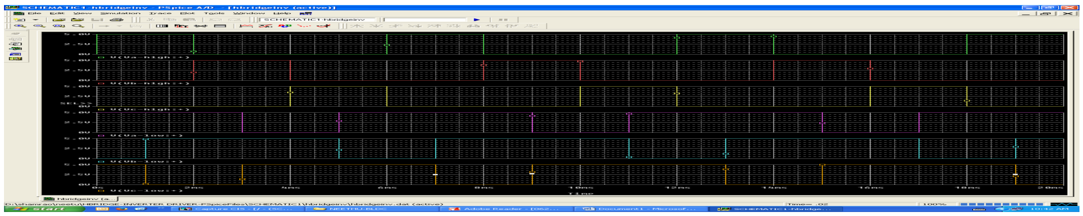

Figure 24. Waveform of 6 PWM input signals to 3-Φ inverter circuit.

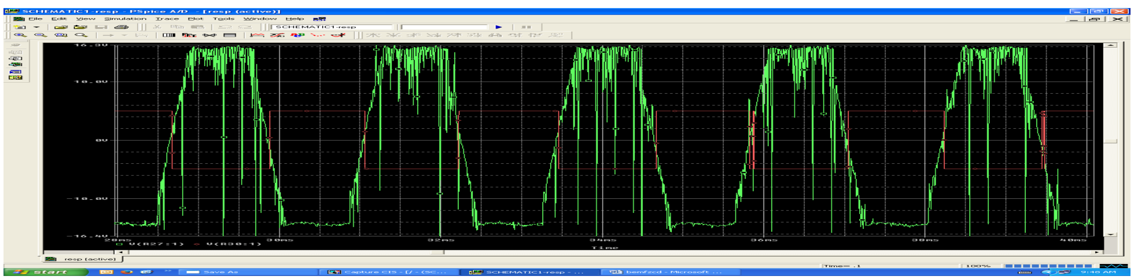

Figure 25. Waveform of BEMF ZCD for modified circuit using real time input.

4. Conclusion

In this paper, a simple technique to detect back EMF for BLDC motor speed controlling for space applications is defined. BLDC motor commutation is done according to the rotor position. Detection of Rotor Position has to be done using sensorless technique that is determining the zero crossing points of BEMF. Zero crossing detection circuit and three phase inverter BLDC motor drive circuit is designed using Or CAD PSpice software. Based on the mathematical model of the BLDCM, the modelling and simulation, for the specified motor is also presented in this paper. Simulation of the proposed method is done by using MATLAB/SIMULINK. The simulation results satisfy the theoretical analysis. Simulation and experimental setup for obtaining back emf voltages are shown which validate the suitability of the proposed method. A fuzzy logic controller (FLC) has been employed for the speed control of BLDC motor. Here BLDC motor modelled in State-Space is very efficiently controlled by Fuzzy Controller. The Simulation of Dynamic performances of Motor at both loaded and not loaded conditions are analyzed and compared. It can be said that Matlab/Simulink is a good tool for modelling and simulation of Fuzzy logic controlled Brushless DC motor. The presented model can be made equivalent to actual system model by incorporating more details of motor and Drivers parameters. The simulation results can be used for implementation of BLDC drive. By adopting Hybrid controller, Adaptive Fuzzy PID controller, artificial neural networks or Neural-Fuzzy controller, performance of BLDC Motor can be improved. Research can be done to add the special sensing winding to the machine to indicate the rotor position.

5. References

1. Gamazo-Real JC, Vázquez-Sánchez E, Gómez-Gil J. Position and speed control of brushless dc motors using sensorless techniques and application trends.Sensors. 2010; 10:6901–47.
2. Rao APC, Obulesh YP, Babu CHS. Performance improvement of BLDC motor with hysteresis current controller. International Journal of Advanced Research in Electrical,

Electronics and Instrumentation Engineering. 2013; 2(12):5900–7.

3. Rajashekar JS, Kumar SCP.Simulation study of MOSFET based drive circuit design of sensorless BLDC motor for space vehicle.International Journal of Current Trends in Engineering and Technology. 2014; 1(1):1–6.
4. Makavana R, Shah BA, Makwana D. Design of fuzzy logic controller for speed regulation of BLDC motor using MATLAB.International Journal for Scientific Research and Development. 2013; 1(2): 391–95.
5. RameshMV, Amarnath J, Kamakshaiah S,Rao GS. Speed control of brushless dc motor by using fuzzy logic PI controller.ARPN Journal of Engineering and Applied Sciences.2011; 6(9):55–62.
6. Singh. CP, Kulkarni SS, Rana SC, Deo K. State-space based simulink modeling of BLDC motor and its speed control using fuzzy PID controller.International Journal of Advances in Engineering Science and Technology. 2012; 2(3):359–69.