Development of Microcontroller Based Speed Control Scheme of BLDC Motor Using Proteus VSM Software

Alok Mukherjee, Susanta Ray, and Arabinda Das
Department of Electrical Engineering, Jadavpur University, Kolkata-700 032
Email: alokmukherjee.ju@gmail.com, raysusant@gmail.com, adas_ee_ju@yahoo.com

***Abstract*—This paper presents a simple way of designing a low cost microcontroller based 3-phase trapezoidal back-emf permanent magnet BLDC motor drive, its simulation and hardware implementation. This controller is intended to drive a BLDC motor at any desired speed and at any load within its rated value. Pulse width modulation (PWM) technique has been adopted for developing 120-degree six-step BLDC motor control algorithm. The microcontroller PIC18F4331 is used to utilize its six dedicated PWM channels for energizing the 3-phases of the BLDC motor. This paper also introduces the application of Proteus VSM (Virtual System Modeling) software as a real-time simulation tool to model the performance of BLDC motor drive following hardware implementation. The Proteus VSM simulation environment is preferred since it enables direct implementation of the compiled program file to the microcontroller both for simulation and hardware model, thus reducing hardware development time. Experimental verification has been carried out to validate the simulated circuit.**

***Index Terms*—BLDC motor, PWM, PIC18F4331 microcontroller, proteus VSM software**

I. Introduction

Electric motors possess an integral part of both the industrial and the domestic sectors. Motors used in abundance are mostly induction motors and brushed DC motors which suffer from low efficiency and high maintenance, respectively. Brushless Direct Current (BLDC) motor has gained immense popularity in recent era due to its ease in control, less maintenance due to the absence of brush-commutator arrangement and higher efficiency [1][2].

They also have high power density especially due to the employment of high energy density permanent magnets used in the rotor. Compared to the most popular induction machine, BLDC motor has lower inertia, allowing faster dynamic response. The only hindrance behind its massive use is the higher cost involved in designing its most imperative controller.

Microcontroller based drive system are nowadays gaining immense popularity for designing cost effective and robust controllers due to its integrated peripherals like PWM generators, Analog to Digital Converter (ADC) etc. [3], lesser requirement of components, increased reliability, very high speed operation, more adaptability to modern control technique and more flexibility of design. In this paper, an attempt has been made for designing a low cost microcontroller based 3-phase trapezoidal back-emf Permanent Magnet BLDC motor drive.

In order to design a BLDC drive, Proteus VSM simulation software [4] has been used as the primary simulation platform. This allows microcontroller programs to be implemented directly to the simulation block, i.e. the program logic can be built using any PIC microcontroller assembler and the program file (hex code) generated after building the logic can be uploaded directly to the microcontroller model available in Proteus. Run time modification of any input data is also allowed in this software. PIC18F4331 microcontroller has been chosen to develop the control algorithm [3][5][6] for driving 3 phase BLDC motors using mostly the modules like 14-bit Power Control PWM Module, Motion Feedback Module and High-Speed 200 Ksps 10-bit ADC module.

The entire drive circuit including the motor model has been designed in Proteus VSM simulation software [4] for direct implementation of the program code. The motor model in Proteus has been calibrated with load to obtain the experimental motor characteristics followed by implementation of a close loop control scheme for variable load constant speed drive. Using this, a prototype has been fabricated and implemented in laboratory to validate the scheme.

II. Operating Principle of BLDC Motor

BLDC motor consists of stator, rotor and position sensor [7] as shown in Fig. 1. Rotation of BLDC motor requires position feedback of relative rotor position. Mostly used BLDC motor uses Hall sensors as the position feedback. In order to produce a rotating field (driving torque), respective phases of stator have to be turned on and off in sequence through the six switches (usually MOSFET of IGBT) of the three phase full bridge inverter, depending on the position of the rotor. Position signals from the three Hall sensors are fed back to the

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controller. Hall signals carry either 0V (logic low) or +5V (logic high) depending on the rotor position.

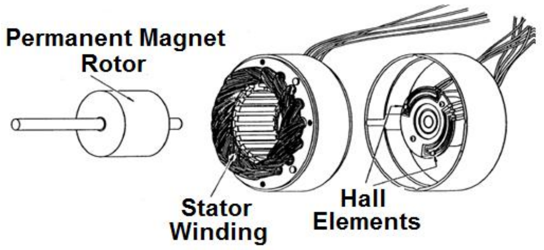

Figure 1. Different parts of BLDC motor

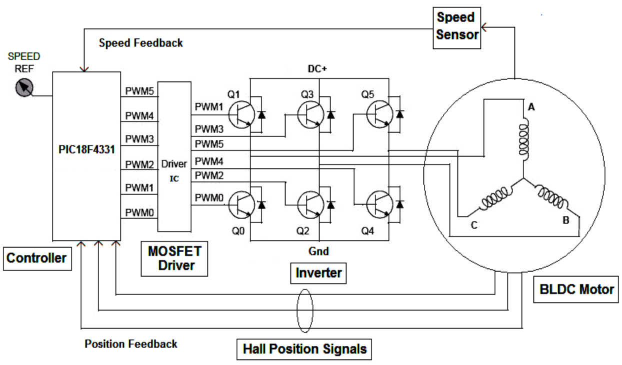

Figure 2. PIC184331 microcontroller based BLDC motor drive

Fig. 2 describes the operation of a BLDC motor drive circuit. Here the digital pulses (bit pattern) from Hall sensors are fed to the microcontroller. External interrupt is generated on each bit change of any of the three Hall position signal inputs. Special interrupt on bit change is an inherent feature of PIC184331 microcontroller which in very useful in designing the motor control algorithm. As soon as any bit change occurs on any of the three Hall input signals, the program execution sequence skips to interrupt address. Another aspect of this particular microcontroller is that it has eight dedicated PWM signals, out of which six PWM signals [8] are required to drive six MOSFET gates of the three phase full bridge inverter. This inverter directly drives the three phases of the BLDC motor. Depending on the rotor position, respective PWM channels are turned on which in turn drive the respective phases of the BLDC stator through the MOSFETs of the inverter. The proper commutation sequence (Clock Wise or Counter Clock Wise) for the respective Hall bit pattern should be stored in a look up table format in the controller itself after carrying out proper experiments on the motor. This sequence allows proper phase energizing for one directional rotation continuously performing electronic commutation. In this present work, PIC184331 microcontroller has been used to incorporate its useful features.

III. Implementation of the BLDC Motor Drive in Proteus VSM

For the ease of understanding, the developed scheme has been sectionalized into the following blocks and presented in Fig. 3.

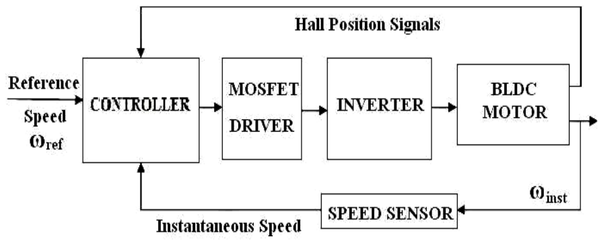

Figure 3. Schematic diagram of BLDC motor drive

BLDC motor: Proteus contains BLDC motor models out of which BLDC-Star type of model is chosen. The motor parameters are embedded in the motor properly by editing its parameters like rotor resistance, inductance, back-emf constant, torque constant etc. The BLDC model parameters were given the same values as obtained from the actual motor under experiment.

Position signals: Information of rotor position is necessary to drive the BLDC motor in a sensored drive scheme. Three electrically equally spaced Hall sensors located over the three stator phases provide this information to the controller. These sensors usually provide either +5V (logic High) or 0V (logic Low) depending on whether the rotor pole is facing the particular sensor or not. In Proteus, sensors are embedded with the motor model and outputs are taken out.

Speed sensor: Speed Sensor senses the motor instantaneous speed. The speed sensor used in drive application is tacho-generator coupled to the motor shaft, which produces a voltage output signal in proportion to the speed of the motor. This voltage output must be scaled in compatibility with the ADC hardware configuration. In Proteus, the motor itself is configured with a tacho-generator in the same model producing an analog voltage signal in proportion to the rotational speed.

Analog to dgital converter (ADC): The microcontroller works with digital logic. So when tacho-generator is used as the speed feedback, the value should be processed digitally before feeding back to the microcontroller. This digital value of speed is then processed by the controller suitably. ADC ICs are well available in 8 bit, 12 bit, 16 bit or may be other higher bit forms, both in practice and in Proteus. In this case, A/D conversion is done by the PIC18F4331 microcontroller itself using the inbuilt 10-bit high speed ADC module. The maximum analog input voltage which the microcontroller can convert to the digital value is +5V, beyond which the digital output remains clamped at maximum value. So the tacho-generator output is scaled accordingly by some resistance voltage divider in such a way that the maximum analog input to ADC channel of the microcontroller reaches nearly +5V corresponding to the maximum speed.

Controller: The controller is the brain of the drive. PIC18F4331 microcontroller has been used here as the basic control block. Depending on the inputs, corresponding PWM channels are generated to drive the inverter. The primary inputs to the controller are the three digital Hall position signals and the tacho-generator speed feedback (analog input). These feedbacks are processed by suitable algorithm (such as Proportional-Integral control, hysteresis control or as in our case, the On-Off control) to run the motor. Thus the primary output from the microcontroller is the PWM switching signals (six in numbers) to drive the six MOSFETs of the inverter to allow electronic commutation at proper instants. Hence, the two most basic tasks of the controller are:

- Maintaining the switching sequence of the six PWM channels to allow proper commutation in synchronism with the Hall position signals.
- Adjust the PWM duty ratio to adjust the output voltage in synchronism with the speed feedback signal.

PIC18F4331 microcontroller is readily available in Proteus. By suitably configuring the microcontroller, it can be successfully operated.

MOSFET driver: It is necessary to apply +12 to +20V at the Gate with respect to the Source of the MOSFET to turn on the MOSFETs successfully. The microcontroller generates a logic "High" signal of +5 Volt dc and logic "Low" at 0 Volt. If the microcontroller pins are connected directly to the MOSFETs, they may not turn on even when the microcontroller PWM pin output is high; hence the gate drivers are required. These driver ICs are configured properly to pull the +5V level to +12 to +15V level, and their outputs are fed directly to the gate of the MOSFETs of the inverter. Thus the PWM chopping signals are transmitted to the MOSFETs from the microcontroller in proper synchronism providing electrical isolation of control circuit from power circuit. Here IC IR2101 has been used to design the motor drive in Proteus.

Inverter: While designing in Proteus, IRFZ44N n-channel MOSFETs have been used in for developing inverter block to drive the BLDC motor directly. Depending on the signal generated from the microcontroller, MOSFET driver transmits appropriate PWM signals to turn on proper MOSFETs of the three phase bridge Inverter in synchronism with the Hall position signals.

IV. Theory of Speed Control by Microcontroller

The speed of the BLDC motor can be controlled almost linearly by controlling the input voltage to the motor. The PIC18F4331 microcontroller consists of eight dedicated PWM channels, out of which only six channels are required for driving the six MOSFETs of the three phase bridge inverter. The PWM switching frequency has been kept high in order to reduce the switching losses, the only limitation being the hardware constraints. Output voltage can be controlled only by adjusting the duty ratio accordingly. In PWM voltage control scheme [8], the output voltage is controlled linearly from the input supply voltage governed by the duty ratio only in following manner:

$$\text{Output Voltage } (V_o) = \text{Duty Ratio } (D) \times \text{Input Voltage } (V_{in})$$

This shows that speed is proportional to the duty ratio of the PWM. In PIC18F4331 Microcontroller, the duty ratio is controlled by assigning proper values of Duty Ratio in the pre-assigned duty cycle registers of each channel.

V. Speed Torque Characteristics from Simulation of Proteus BLDC Model

The Speed Torque Characteristics of an ideal BLDC Motor is drooping in nature as shown in Fig. 4.

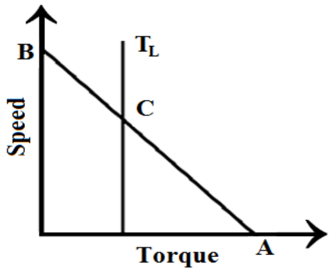

Figure 4. Speed-Torque characteristic of ideal BLDC motor

Here, the point C denotes the point of intersection of any load torque T_L with the electromagnetic torque line AB.

On application of a voltage, the motor starts at point A with the applied load torque T_L. Since at this point Electromagnetic Toque (T_E) is higher than the load torque (T_L), the motor accelerates up to point C where the two torques (T_L and T_E) become equal. During this shifting of operating point from A to C, the acceleration of the motor decreases gradually as the accelerating torque (T_E - T_L) gradually reduces. Even if the motor accelerates beyond point C, T_L now becomes higher than T_E, thus the motor decelerates again and comes back to point C. Thus for a specific load T_L, C becomes the stable operating point. Hence it is essential to know the motor speed-torque characteristics in order to design the controller, because once the motor characteristics are known, it becomes easier to predict the motor output, loading the motor with desired percentage of rated load, design the controller for speed control application and draw proper inference. This is achieved by performing a few experimental steps on the BLDC motor model under experimentation in Proteus VSM as discussed in the next section.

VI. Speed Torque Characteristics of BLDC Motor from Proteus BLDC Motor Model

The speed torque characteristics of an ideal BLDC motor is a straight line. The actual curve deviates from the ideal in a slight non-linear way, although the degree of non-linearity is not known beforehand. With a view to design the controller, the knowledge of exact characteristics is absolutely necessary; especially for loading the motor model fully or partially, the knowledge of maximum and rated load is absolutely necessary. In Proteus, load torque is provided in the form of voltage to the motor. Hence, in order to calibrate the load and to obtain the actual speed torque characteristics of the motor model, the motor is subjected to load, varying in steps and the corresponding speeds were noted. These results are plotted to form the motor model speed-torque characteristics. This is done as follows:

- The motor is run at no load with rated voltage applied. Since load torque was absent ($T_L = 0$), the motor accelerated to its maximum speed. Thus the operating point *B* is obtained (Fig. 5).
- Next, the motor is loaded higher gradually (by increasing the voltage connected to the load terminal of the BLDC motor model) and tested for which minimum load (in terms of voltage) the motor steady state speed becomes zero. It is found that for a certain load, the motor started to accelerate, but due to the application of the heavy load, the motor speed started falling immediately and after a few oscillations about the zero speed, it settled to zero (Fig. 6). This phenomenon is called stalling. Thus point *A* is obtained. Rated load (in terms of voltage) is assigned 30% of this stalling torque.
- Apart from the above two steps, the motor is gradually loaded in steps of 5% from no load (point *B*) to the maximum load (point *A*) and the corresponding speeds are plotted to obtain the actual BLDC motor model speed-torque characteristics which is slightly hyperbolic in nature and very close to the ideal straight line characteristics (Fig. 5).

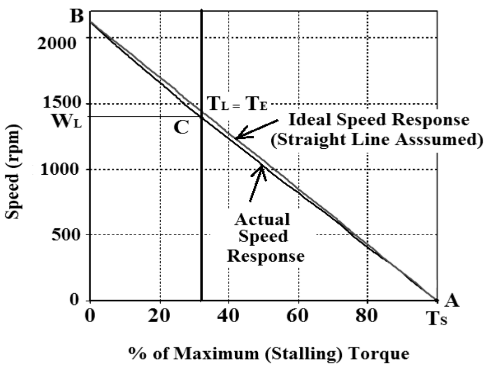

Figure 5. Proteus simulated speed torque characteristics of BLDC motor

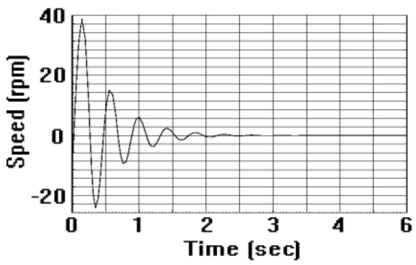

Figure 6. Speed response during stalling of BLDC motor

VII. Close Loop Control Strategy by Simple Voltage Control

The speed-torque characteristic of an ideal BLDC motor is linear and has been shown in Fig. 4. For load torque T_L and applied voltage V_1 the motor operates with the operating point *C* on speed-torque characteristic and runs with the speed *OG*. This is the open loop speed control scheme. It has already been mentioned that after the application of voltage, the motor starts from point *A* and reaches point *C* following the curve *AB* due to its inherent characteristics.

For a fixed load torque, BLDC motor can be operated in close loop at any desired speed less than the speed corresponding to the applied load torque. Suppose the motor is to be operated with the load torque T_L and with the set speed indicated by *OS* (Fig. 7). Here after starting, when the motor traverses the path *AB* and reaches the point *E*, the controller judges that this speed OS' is very close to *OS*, the set speed.

At this point T_E is still greater than T_L. Hence T_E must be reduced to make it equal to T_L to achieve the desired speed. One way to reduce T_E is to reduce voltage level. This can be done by designing a controller for reducing voltage level.

For the reduction of voltage from V_1 to V_2 at point *E*, motor traverses the path *ED* and reaches the operating point *D* and runs with the set speed maintaining the same load torque.

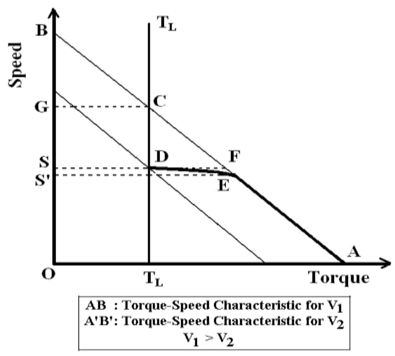

Figure 7. Closed loop control strategy from speed torque characteristics of BLDC motor

VIII. Basic ON-Off Control Algorithm

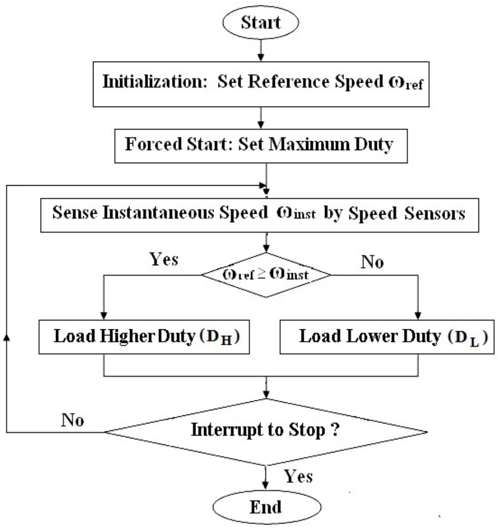

Figure 8. Flowchart for simple On-Off control strategy

The simplified on-off control strategy [1] [2] [9] [10] applied here is shown in Fig. 8 following the predicted step response of speed. The controller simply switches between two voltage levels as shown depending on the instantaneous speed of the motor. Hence the steady state speed is regulated within a particular speed band (Fig. 9).

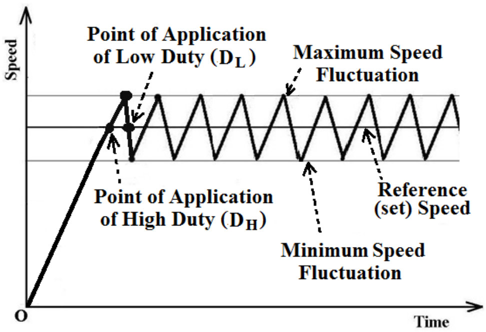

Figure 9. Simple On-Off control strategy

IX. Simulation Results

The entire BLDC Motor drive scheme has been implemented in Proteus VSM simulation software [4] and is shown in Fig. 10.

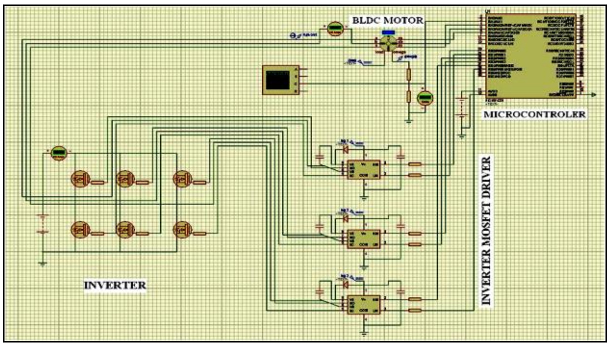

Figure 10. Proteus simulated BLDC Motor Drive

PWM scheme has been used here to control the voltage at the BLDC motor input terminal. This PWM signals have been generated by PIC18F4331 microcontroller.

Simple On-Off Control Algorithm has been implemented to adjust the duty ratio according to the requirement for close loop control to reach the desired speed at any load within the rated value. Fig. 11 shows the back emf of the three phases of the BLDC motor model monitored by using the inbuilt digital oscilloscope.

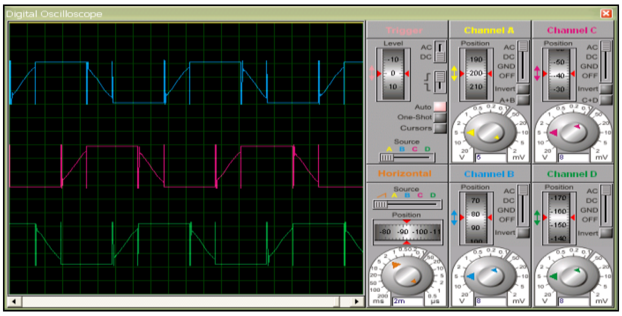

Figure 11. Three phase back emf

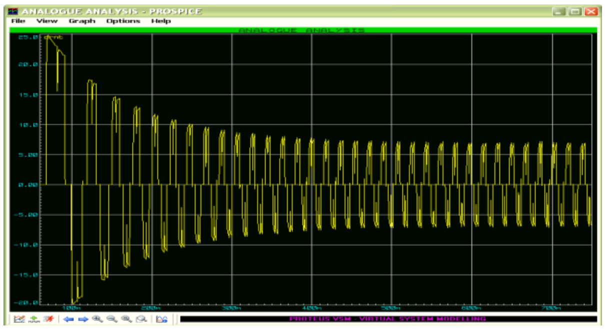

Figure 12. Current response oscillogram

Fig. 12 shows the phase current waveform obtained by using the software inbuilt analog analyzer and Fig. 13 is a magnified representation of the Fig. 12. The control algorithm is implemented using MikroC Pro assembler and embedded directly in Proteus, and later in actual hardware circuit. The close loop speed response obtained is shown Fig. 14. Current responses for different loads are shown in Fig. 15-Fig. 17.

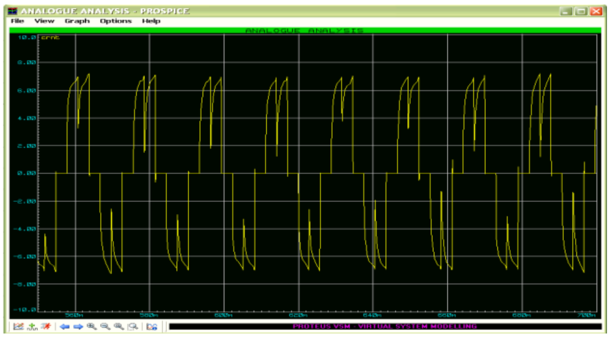

Figure 13. Current response oscillogram (magnified)

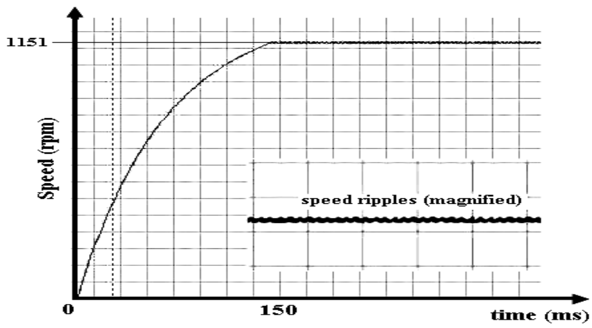

Figure 14. Simulation result for step response of speed of BLDC motor on full load torque (1151 rpm)

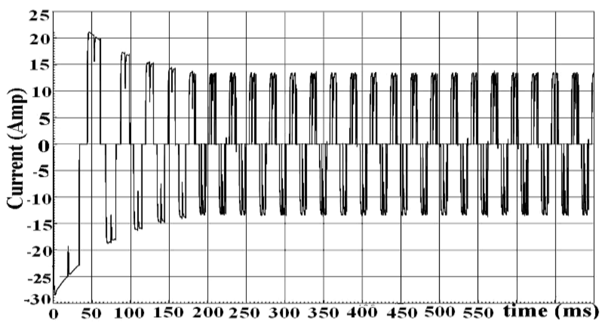

Figure 15. Simulation result for phase current response of BLDC motor on full load **(**1151 rpm)

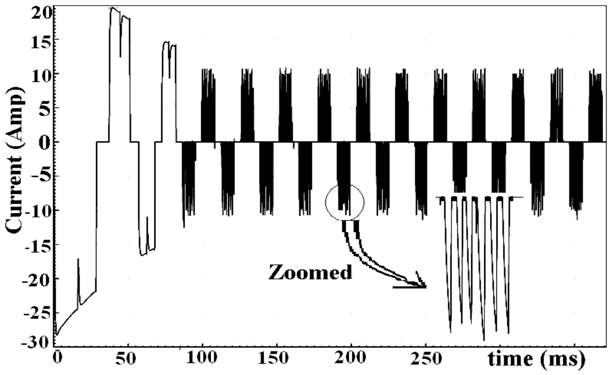

Figure 16. Simulation result for phase current response of BLDC Motor employing On-Off controller on 30 % full load (1153 rpm)

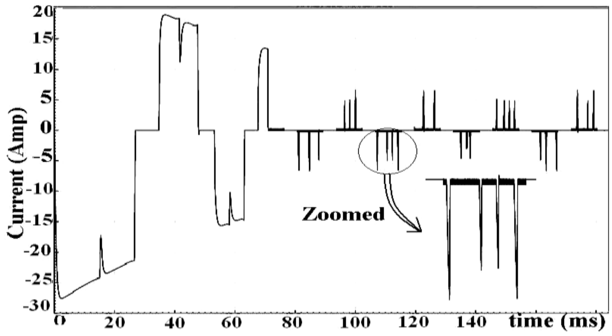

Figure 17. Simulation result for phase current response of BLDC motor employing On-Off controller on load (1153.5 rpm)

X. Experimental Verification

The driver circuit consists mainly of microcontroller module, MOSFET driver and three-phase inverter. The hardware design is implemented in consistency with the simulated circuit [11]. The modified adaptive On-Off algorithm has been applied to run a 24V, 180W, 3000 rpm BLDC motor. Hardware results were collected using two-channel Digital Storage Oscilloscope. The oscilloscope is used to observe and measure the speed in terms of tacho-generator output, PWM signals, Hall sensor signals and back emf. Fig. 18 and Fig. 19 show respectively the results of back emf and closed loop speed response of the BLDC motor.

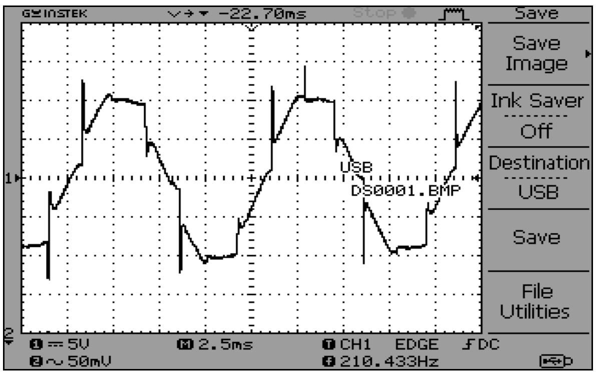

Figure 18. Back emf oscillogram obtained from experiment

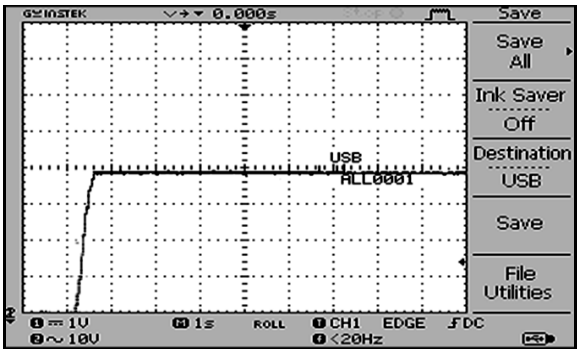

Figure 19. Step response of speed of BLDC motor on 30% full load obtained from experiment at 1130 rpm

XI. Conclusion

The BLDC motor drive model has been developed both in simulation and hardware realizations for low-power applications. This investigates the motor drive performance for 120-degree commutation switching technique by On-Off control algorithm for variable torque - constant speed applications. The controlling method is a sensored type in which low cost PIC18F4331 microcontroller acts as the main controlling unit. The introduction of Proteus VSM shows its capability and usefulness in designing virtual model, selection of appropriate ICs and other equipments and the troubleshooting before hardware circuit construction, thus requiring a shorter product development time. Experimental verification has also been carried out. Besides, the cost effectiveness of this low cost controller must possess good commercial appeal for low power application.

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Alok Mukherjee was born in Kolkata in 1987. He received his Bachelor Degree in Electrical Engineering from Jadavpur University, Kolkata in 2010. Now he is a student of Master of Electrical Engineering with specialization in Machines and Drives in Jadavpur University. His field of interest includes Microcontroller based control of Electrical Machines and Drives, modelling and simulation of Electrical Machines and Power System Operation.

Susanta Ray was born in 1980. Presently he is Asstant Professor in the Electrical Engineering Department, Jadavpur University. Before joining in Jadavpur University in 2009 he has worked as a Scientist in Defence Research Development Laboratory, Hyderabad since 2007. He obtained his B.E. and M. E. degrees in 2002, 2008 respectively in Electrical Engineering from Jadavpur University. His field of interst includes Development of embedded systems, microcontroller based control, machine and drives etc. Mr. Ray published a good number of research articles related to application of microcontroller in electrical engineering in International journals.

Arabinda Das has born in 1966. He obtained his B. Tech., M. Tech. and Ph.D. (Tech.) degrees in 1990, 1992 and 2000 respectively in Electrical Machines and Power System from the University of Calcutta. Presently he is Associate Professor in the Electrical Engineering Department, Jadavpur University. Before joining in Jadavpur University in 1999 he has worked as a Lecturer in Regional Engineering College, Durgapur since 1996. He has published a number of research articles related to application of microprocessor / microcontroller in electrical engineering in National and International journals and conferences. He is the receipent of Railway Board Prize, The Union Ministry of Energy --- Department of Power Medal, The Corps of Electrical and Mechanical Engineers Medal from The Institution of Engineers (India) etc. Dr. Das is the member of The Institution of Engineers (India) and fellow of The Institution of Electronics and Telecommunication Engineers.

