

# DESIGN AND REAL TIME IMPLEMENTATION OF CONTROL ALGORITHM FOR PERMANENT MAGNET BRUSHLESS DC MOTOR

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## **Abstract**

*This paper presents the simulation and implementation of three phase inverter fed Permanent Magnet Brushless DC(PMBLDC) Motor drive in the presence of hall sensor . The switching angle for the pulse is selected in such way to reduce the harmonic distortion. This drive system has advantages like reduced total harmonic distortion and higher torque. The module of the Three phase inverter system controlled Permanent magnet Brushless DC motor is simulated and implemented. The experimental results are compared with simulation results.*

*Keywords: Three Phase, Inverter, PMBLDC, Bi-directional switch, Hall sensors, Sim Power system.*

## **I INTRODUCTION**

Majority of the electrical drives operate with variable speed. These drives require variable voltage high power converters. Hence, the interest is oriented towards multi-level converters. The Permanent Magnet Brushless DC (PMBLDC) motor is also referred to as an electronically commutated motor [2] . There are no brushes on the rotor and the commutation is performed electronically at certain rotor positions. The stator magnetic circuit is usually made from magnetic steel sheets. The magnetization of the permanent magnets and their displacement on the rotor are chosen, such that the back emf shape is trapezoidal [8].The PMBLDC motor at fractional and integral horse power levels often run off the line with rectifier-inverter based system, typically with nearly rectangular output current waveforms [12]. Such non-sinusoidal excitation waveforms can also increase the torque per ampere realizations with particular motor designs. PMBLDC motor are generally controlled using a three phase inverter, requiring a rotor position sensor for starting and for providing the proper commutation sequence to control the inverter [8]. With the growing use of inverters the problem of injected harmonics becomes critical.

Simple commutation method for PMBLDC motor used in Speed Servo System was proposed [23].

A new speed control strategy of a PMBLDCM drive is proposed using the reference speed as an equivalent reference voltage at DC link. The speed control is directly proportional to the voltage control at DC link was proposed [20]. Provided a radial core type brushless direct-current motor and having an excellent assembly capability of division type stator cores in a double rotor structure [10]. The Speed of the proposed PMBLDCM drive is controlled to improve efficiency.

The commutation of a PMBLDC motor is controlled electronically. To rotate the PMBLDC motor the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. The position sensors are Hall sensor, variable reluctance sensor and accelerometer.

The importance of mounting Hall sensors into the stationary part of the motor was discussed [16]. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors with respect to the rotor magnets will generate an error in determination of the rotor position. The Hall sensors are normally mounted on a printed circuit board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors to align with the rotor magnets in order to achieve the best performance.

A new position sensor, such as a three branches vertical Hall sensor was proposed [3] Four possible switching patterns are proposed by modulating only upper/lower switches. Dummy Hall sensor signals where generated for variable speed reference with the help of micro-controller to analyse inverter voltages [19]. The high performance speed or position control requires an accurate knowledge of rotor shaft position and velocity in order to synchronize the phase excitation pulses to the rotor position. This implies the need for speed or a shaft position sensor such as an optical encoder or a resolver. However, the presence of

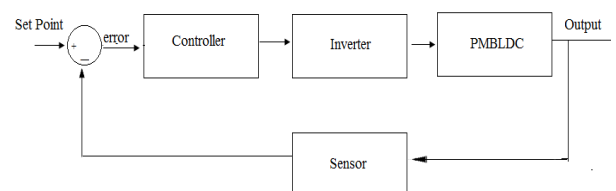
this sensor (expensive and fragile and require special treatment of captured signals), causes several disadvantages from the standpoint of drive cost, encumbrance, reliability and noise problem. The Method of observers is sometimes more favourable due to its robustness to parameter variations and its excellent disturbance rejection capabilities [1]. The initial position of the permanent magnet is identified by the time periods of discharge of stator windings, which are excited before discharge. This technique does not cause any rotation during detection. The extraction of rotor position information by indirectly sensing the back-EMF from only one of the three motor-terminal voltages for a three-phase motor was given [4]. By using machine parameters and equations, reference frame theory and transformations to calculate position and speed was given [5]. In field-oriented operation of the PMBLDC, phase back-EMF is aligned with phase current. Switching instants of the converter was obtained by knowing the zero-crossing of the back-EMF and a speed-dependent period of time delay was given [6]. Novel Direct Back EMF detection for sensorless PMBLDC Motor drives was proposed [7]. The state of the system is produced as the output. The observer-produced state is then fed back into the system as would be the actually measured variables as used in a closed-loop system control. The reduced-order observers to estimate the back-EMF which is used to obtain rotor position and speed [11].  $H_2$  and  $H_\infty$  controls were proposed [13], for a sensorless permanent magnet synchronous drive system. An adaptive control was proposed [13]. The sensorless technique by model's prediction of a voltage or current and the actual value was proposed [15].

This method is not as sensitive to phase delay as the zero-crossing method, as the frequency to be filtered is three times as high. The reactance of the filter capacitor in this case dominates the phase angle output of the filter more so than with the lower frequency. On the other hand, greater than 213 stator winding pole pitch is required. The third harmonic of the rotor flux can link the stator winding and induces a third harmonic voltage component which can be detected between the motor neutral and the negative inverter bus terminal. The third harmonic flux linkage lags the third harmonic of the phase back-EMF voltages by 30 degree. The zero crossings of the third harmonic of the flux linkage corresponds to the commutation instants of the BLDC motor. To acquire correct commutation instants, sensing the positive or negative going zero-crossing of the back-EMF is essential. The third harmonic method provides a wider speed range (100-6000 rpm) than the zero-crossing method, does not introduce as much phase delay as the zero-crossing method and requires less filtering. Sensorless flux weakening

control of PMBLDC machines using third harmonic back-EMF was given [20]. This technology provides great reduction in filter size and output impedance, while maintaining the power factor at the desired level. The power factor corrected (PFC) buck bridge DC-DC converter for a permanent magnet brushless DC motor (PMBLDCM) for an air conditioner was proposed (Singh and Singh 2010). Simple commutation method for PMBLDC motor used in Speed Servo System was proposed [23]. A new speed control strategy of a PMBLDCM drive is proposed using the reference speed as an equivalent reference voltage at DC link. The speed control is directly proportional to the voltage control at DC link was proposed [22]. FPGA Based Reduced Switch Three Phase Inverter Fed Induction Motor Drive was proposed [9].

In this method permanent magnet is fixed at the end of a rotary shaft and the magnetic sensor is placed below. The magnet creates a magnetic field parallel to the sensor surface. This surface corresponds to the sensitive directions of the magnetic sensor. Three-phase brushless motors need three signals with a phase shift of  $120^\circ$  for control. Hence, a closed-loop regulation may be used to improve the motor performance. This sensor automatically creates three signals with a phase shift of  $120^\circ$ , which directly correspond to the motor driving signals, to simplify the motor control in a closed-loop configuration.

The basic block diagram of PMBLDC drive is shown in Figure 1. The three phase inverter at the input side acts like an electronic commutator that receives switching logical pulses from the absolute position sensor. The PMBLDC drive is commonly



known as electronically commutated motor (ECM).

**Figure 1 Basic Block diagram of PMBLDC Drive**

## **II MODELLING OF PMBLDC MOTOR AND INVERTER**

The PMBLDC motor is modeled in the stationary reference frame using 3-phase abc variables [17]. The volt -ampere equation for the circuit shown in the Figure 2 can be expressed as given in Equations (1) to (3).

$$v_{an} = Ri_a + \frac{d\Phi_a}{dt} + e_{an} \quad (1)$$

$$v_{bn} = Ri_b + \frac{d\Phi_b}{dt} + e_{bn} \quad (2)$$

$$v_{cn} = Ri_c + \frac{d\Phi_c}{dt} + e_{cn} \quad (3)$$

where  $v_{an}$ ,  $v_{bn}$  and  $v_{cn}$  are phase voltages where values are given in Equation (4)

$$V_{an} = V_{ao} - V_{no}, V_{bn} = V_{bo} - V_{no}, V_{cn} = V_{co} - V_{no} \quad (4)$$

where  $V_{ao}$ ,  $V_{bo}$ ,  $V_{co}$  and  $V_{no}$  are three phase and neutral voltages referred to the zero reference potential at the mid- point of dc link as shown in the Figure 2.

$R$  is the resistance per phase of the stator winding

$\frac{d}{dt}$  - is the time differential operator and  $e_{an}$ ,  $e_{bn}$  and  $e_{cn}$  are phase to neutral back-EMFs. The  $\Phi_a$ ,  $\Phi_b$  and  $\Phi_c$  are total flux linkage of phase windings a, b and c respectively. These values can be expressed as given in Equations (5) to (7)

$$\Phi_a = L_s i_a - M (i_b + i_c) \quad (5)$$

$$\Phi_b = L_s i_b - M (i_a + i_c) \quad (6)$$

$$\Phi_c = L_s i_c - M (i_a + i_b) \quad (7)$$

where  $L_s$  and  $M$  are the self and mutual inductance of the stator coil respectively. The PMBLDC motor has no neutral connection hence, we have

$$i_a + i_b + i_c = 0 \quad (8)$$

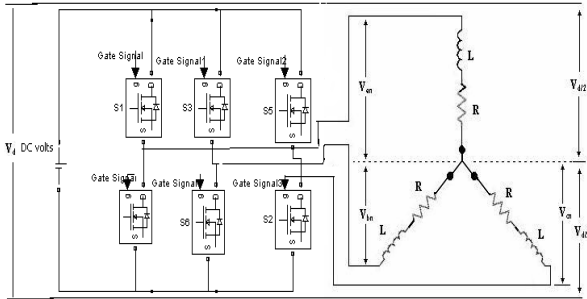
Substituting Equation (8) in the Equations (5) to (7), the flux linkages can be rewritten as given in Equations (9) to (11)

$$\Phi_a = i_a (L_s + M) \quad (9)$$

$$\Phi_b = i_b (L_s + M) \quad (10)$$

$$\Phi_c = i_c (L_s + M) \quad (11)$$

By substituting the Equations (9) to (11) in volt ampere Equations (1) to (3) and rearranging them in a current derivative of state space form, we get



**Figure 2 Three Phase Inverter fed PMBLDC Motor**

$$\frac{di_a}{dt} = \frac{1}{(L_s + M)} [V_{an} - Ri_a - e_{an}] \quad (12)$$

$$\frac{di_b}{dt} = \frac{1}{(L_s + M)} [V_{bn} - Ri_b - e_{bn}] \quad (13)$$

$$\frac{di_c}{dt} = \frac{1}{(L_s + M)} [V_{cn} - Ri_c - e_{cn}] \quad (14)$$

The developed electromagnetic torque can be expressed as given in Equation (15)

$$T_e = [e_{an}i_a + e_{bn}i_b + e_{cn}i_c] / \omega_r \quad (15)$$

where  $\omega_r$  is the rotor speed in electrical rad/seconds.

$$\frac{d\omega_r}{dt} = (P/2) \frac{(T_e - T_L - B\omega_r)}{J} \quad (16)$$

where  $P$  is the number of poles,  $T_L$  is the load torque in N-m,  $B$  is the frictional co-efficient in N-ms/rad, and  $J$  is the moment of inertia in kg-m<sup>2</sup>.

The derivative of the rotor position ( $\theta_r$ ) in state space form is expressed as given in Equation (17)

$$\frac{d\theta}{dt} = \omega_r \quad (17)$$

The potential of the neutral point with respect to the zero potential ( $v_{no}$ ) is required in order to avoid imbalance in the applied voltage and simulate the performance of the drive. This neutral point voltage is obtained by substituting Equations (8) in the volt-ampere Equations (1) to (3) and adding them together. Hence,

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = R(i_a + i_b + i_c) + (L_s + M) (di_a/dt + di_b/dt + di_c/dt) + (e_{an} + e_{bn} + e_{cn}) \quad (18)$$

Substituting Equation (8) in Equation (18) and simplifying we get,

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = (e_{an} + e_{bn} + e_{cn}) \quad (19)$$

The Equation (19) can be rewritten as given in Equation (20)

$$v_{no} = [v_{ao} + v_{bo} + v_{co} - (e_{an} + e_{bn} + e_{cn})] / 3 \quad (20)$$

The set of differential equations mentioned in Equations (12) to (14) and (16) to (20) define the model developed in terms of the variables  $i_a$ ,  $i_b$ ,  $i_c$ ,  $\omega_r$ ,  $T_e$  with time as an independent variable.

### 2.1 Modelling Of Back - Emf Using Rotor Position

The per phase back- EMF in the PMBLDC motor is trapezoidal in nature and are the functions of the speed and rotor position angle ( $\theta_r$ ). The phase back-

Emf  $e_{an}$  can be expressed as given in Equations (21) to (24)

$$e_{an} = E \quad 0^\circ < \theta_r < 120^\circ \quad (21)$$

$$e_{an} = (6E/\pi) (\pi - \theta_r) - E \quad 120^\circ < \theta_r < 180^\circ \quad (22)$$

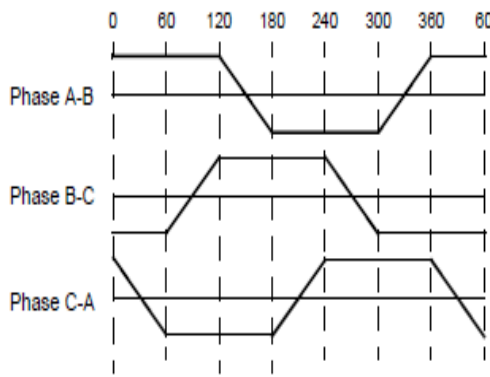
$$e_{an} = -E \quad 180^\circ < \theta_r < 300^\circ \quad (23)$$

$$e_{an} = (6E/\pi) (\theta_r - 2\pi) + E \quad 300^\circ < \theta_r < 360^\circ \quad (24)$$

where  $E = K_b \omega$ .

and  $e_{an}$  can be described by E as shown in Figure 3.

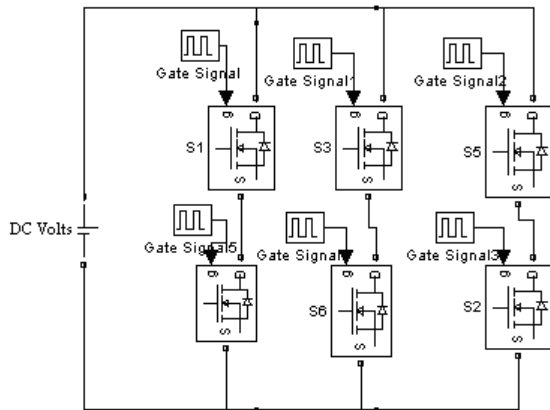
The back-Emf functions of other two phases  $e_{bn}$  and  $e_{cn}$  are defined in similar way using E.



**Figure 3 Phase Back- EMF of Three Phase Voltage**

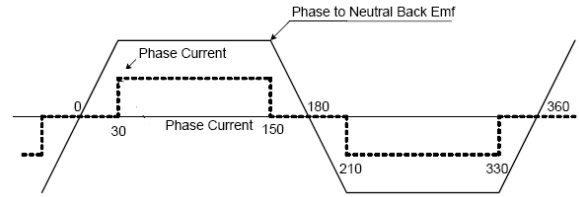
## 2.2 Three Phase Inverter Fed PMBLDC Motor

The three phase inverter circuit is shown in Figure 4. The MOSFET is used as a switch, which can operate at high switching frequency. This feature is helpful in driving the motor at high current and low voltage conditions. Each MOSFET conducts for a duration of 120 degrees. When using a VSI, the desired current profile is achieved by controlling the switching of the MOSFET. The gating signals given to the MOSFET are sequenced to every 60 degree interval.



**Figure 4 Three Phase Inverter**

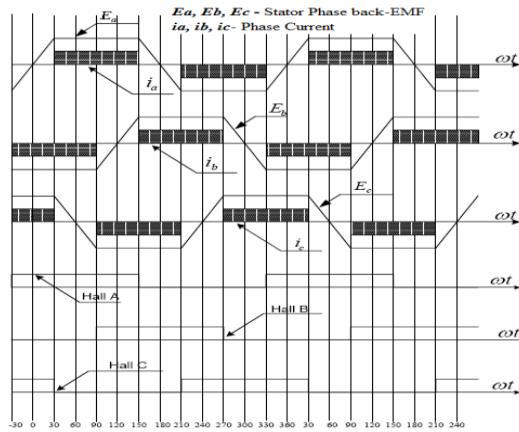
At any given time, only *two* switches out of the six switches of an inverter are conducting. This means that only two phases are conducting at any instant, with current entering in one of the phases and leaving through the other. The convention used in this thesis is that, the current entering any phase of a motor is assigned a positive sign and the current that is leaving any phase of a motor is assigned a negative sign. Therefore, the upper switches of the inverter, namely,  $S_1$ ,  $S_3$  and  $S_5$ , carry a current (flowing into the motor) which is assigned a positive sign. The lower switches of the inverter, namely,  $S_2$ ,  $S_4$  and  $S_6$  carry a negative current (flowing out from the motor).



**Figure 5 Variation of Phase Back- EMF and Phase Current**

The back-EMFs, stator phase currents and Hall sensor outputs are as shown in Figure 5. It is seen clearly that there is a definite relation between the back-EMFs and the current waveforms, as a function of the rotor position. Hence, to have proper operation of PMBLDC motor, it is necessary to synchronize the phase currents with the phase back -EMFs. This is achieved by the use of Hall position sensors which detect the position of the rotor field and hence the position of the rotor shaft. Corresponding to the rotor field, the Hall position sensors output a combination of binary numbers. A motor with synchronized switching is able to produce a positive torque.

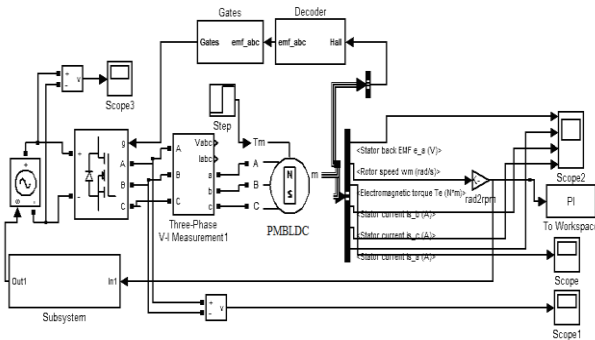
Figure 6 depicts the definite sequence in which the phases conduct and turn off. The current commutation from one phase to the other phase corresponding to that particular state of the back- EMF is synchronized by the Hall position sensors, and it occurs after every sixty electrical degrees. It takes a finite interval of time for commutation, to transfer the current from one phase to the other phase in the appropriate sequence.



**Figure 6 PMBLDC Stator Phase Back-EMFs, Stator Phase Currents and Hall Sensor Outputs**

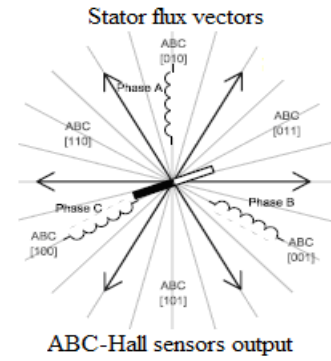
### 2.3 Voltage Control Method Using PI Controller

The closed loop speed control system of a PMBLDC motor using voltage control method with PI controller uses speed regulator to control the DC bus voltage is as shown in Figure 7. The three phase inverter fed PMBLDC motor uses MOSFET as the switch.



**Figure 7 Simulink Diagram for Speed Control of PMBLDC Motor Using PI Controller**

Two control loops are used to control the speed of PMBLDC motor, in which the inner loop synchronizes the output of the inverter with the back EMF of the motor. The outer loop controls the speed of the motor, by varying the DC bus voltage using PI controller. The actual speed of the motor is compared with its reference value and the error in speed is processed by the PI controller. The output of PI controller is applied as the input voltage. The stator voltage to the motor is varied in linear proportion to the supply frequency to maintain the flux at a constant value. Hall sensors are used to identify the rotor position. The gates of the inverter are controlled by the Hall effect switches, passing through a gates decoder.



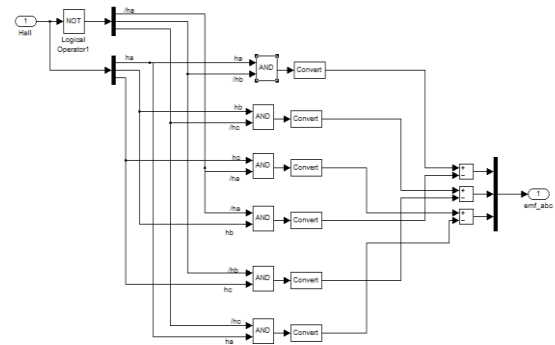
**Figure 8 Stator Flux Vectors**

The Hall sensors generate  $2\pi/3$  angle phase shifted square waves. These waves are in phase with the respective phase voltage. Each of Hall sensor states correspond to a certain stator flux vector. The Hall sensor states with corresponding stator flux vectors are illustrated in Figure 8. The same information is detailed in Table 1.

**Table 1 Truth Table Representation of Stator Vector Flux**

Hall Sensor A	Hall Sensor B	Hall Sensor C	Emf_a	Emf_b	Emf_c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

The decoder circuit is shown in Figure 9. This circuit uses logical AND gates and generates EMFs based on the Hall sensor signals.



**Figure 9 Decoder Circuit**

**Table 2 Electronic Commutator Output Based on Hall Sensor Signals**

Emf_a	Emf_b	Emf_c	S <sub>1</sub>	S <sub>2</sub>	S <sub>3</sub>	S <sub>4</sub>	S <sub>5</sub>	S <sub>6</sub>
0	0	0	0	0	0	0	0	0
0	-1	+1	0	0	0	1	1	0
-1	+1	0	0	1	1	0	0	0
-1	0	+1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
+1	-1	0	1	0	0	1	0	0
0	+1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

Three upper switches of the inverter are turned on sequentially in the middle of the respective positive voltage half-cycles. The lower devices are chopped in sequence for  $2\pi/3$  angles in the respective negative voltage half cycles with the help of decoder for controlling the current.

#### 2.4 Motor Specifications

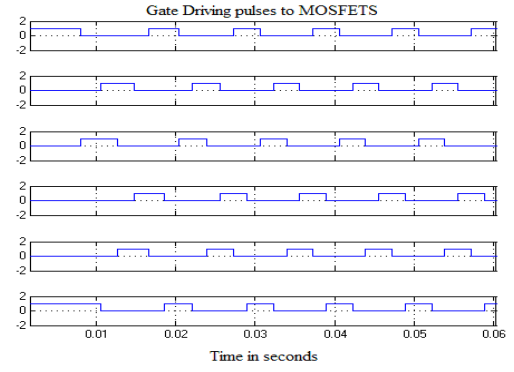
The PMLDC motor specification is given in Table 3.

**Table 3 PMLDC Motor Specification**

Type	Trapezoidal Motor
Voltage	415 Volts
Stator Resistance	18.7 ohms
Inductance	0.02682 H
Flux Induced By Magnets	0.1717 wb
Friction Factor	1.349e-005
Pole Pairs	4
Back Emf	Trapezoidal
RatedSpeed	1500 rpm

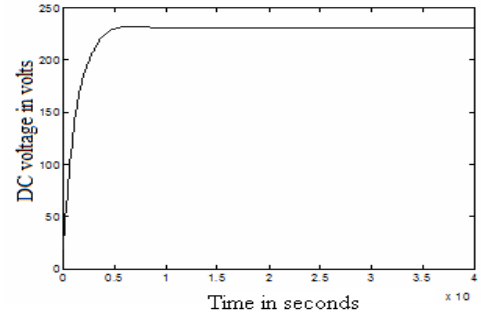
#### 2.5 Simulation Results

The gate driving pulses to the MOSFETs is shown in Figure 10. These driving pulses make the MOSFET to conduct in 120 degree mode of conduction and remains in off condition for the 240 degrees. Successive base drives are delayed by 60 degrees. Six intervals are present for one cycle.



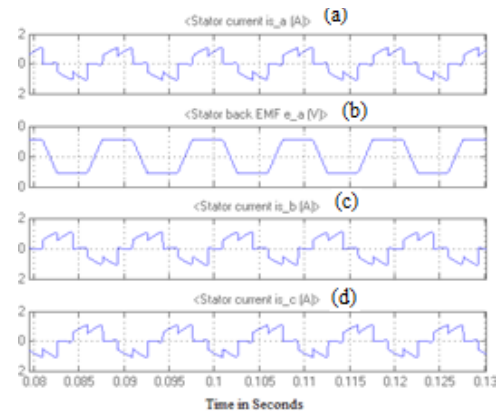
**Figure 10 Gate Driving Pulses**

Figure 11 shows the output of controlled voltage source which is fed to three phase inverter. The PI controller takes about 6 seconds to maintain a constant input voltage to an inverter when there is a speed variation.



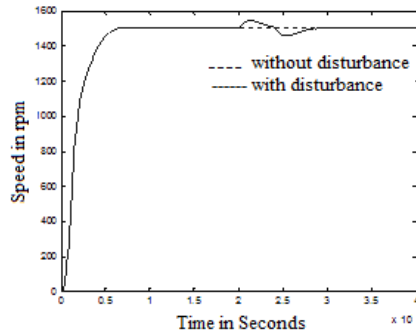
**Figure 11 DC Voltage to Inverter**

The simulation results of stator current are shown in Figure 12 (a) to (d). The currents are quasi square wave with a displacement of  $120^\circ$ . The stator phase back-EMF is shown in Figure 12(b). The phasor back-EMF is trapezoidal as shown and is in phase with stator phase current.



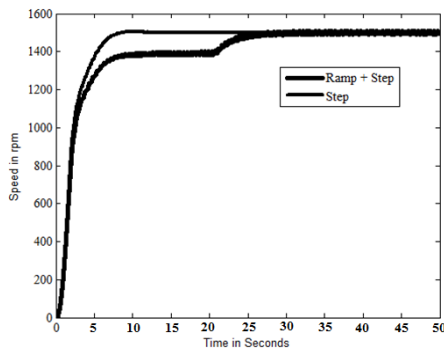
**Figure 12 (a) Stator Phase Current  $i_a$   
(b) Phase Back-EMF in Phase a  
(c) Stator Phase Current  $i_b$   
(d) Stator Phase Current  $i_c$**

The speed response curve with and without disturbance using PI controller with step load is shown in Figure 13. Load disturbance is applied at  $t = 20$  seconds. The PI controller is capable of tracking the desired speed at  $t = 27$  seconds with a delay of 7 seconds to reach the desired speed.



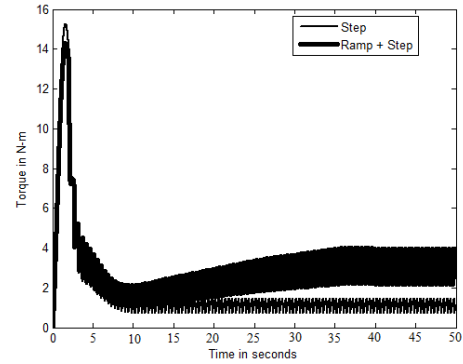
**Figure 13 Variation of Speed Response with and without Disturbance with Step Load**

The simulation carried out in the presence of Ramp followed by Step load without disturbance is given in Figure 14. The variation in speed with ramp followed by step has larger amount fluctuation in speed as compared to Step load. The settling time is almost equal for both the load variation.



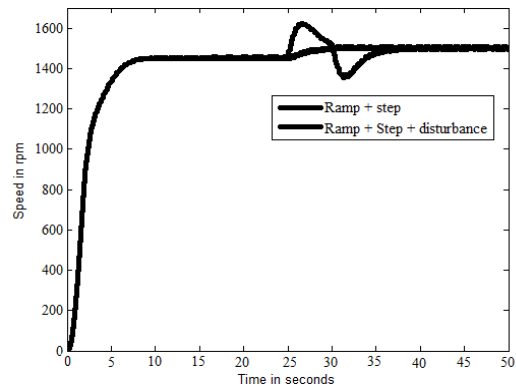
**Figure 14 Variation of Speed Response with Ramp + Step and Step Load**

Figure 15 shows the variation of torque for Step load and Ramp followed by Step load. While using Step load the torque increases to nearly 15 N-m when the motor starts and stabilizes rapidly when the motor reaches the reference value.



**Figure 15 Comparison of Variation in Torque Ramp+ Step and Step Load**

The speed variation curve with and without disturbance using Ramp followed by Step load is shown in Figure 16. Load disturbance is applied at  $t = 25$  seconds. The PI controller is capable of tracking the desired speed at  $t = 37.5$  seconds. It takes 12.5 seconds delay to reach the desired speed.



**Figure 16 Comparison of Variation in Speed of PMBLDC Motor in the Presence of Load Disturbance**

Performance measures of PMBLDC motor using PI controller is depicted in Table 4.

**Table 4 Performance measures of PMBLDC motor using PI controller**

Performance measures	PI
Settling time ( $T_s$ ) in seconds	6.3
RMS current in amperes	3.5
IAE	42.79
ISE	334
THD in %	0.5747



### 3. Real Time Implementation Of Control Strategies on PMLDLC Motor

Experimental investigations of PI control schemes developed are presented in this section. The speed control in the presence of hall sensor with PI control are implemented on the PMLDLC motor experimental setup and the performance are analysed.

#### 3.1 Experimental Setup

The experimental set up for speed control of PMLDLC motor in the presence of Hall sensor for position sensing is shown in Figure 17. The setup consists of Micro-2407 trainer, Inverter module, BLDC motor and Hall sensor signal conditioner. The Micro-2407 a 16-bit fixed point DSP trainer based on TMS320LF2407A DSP Processor is used.

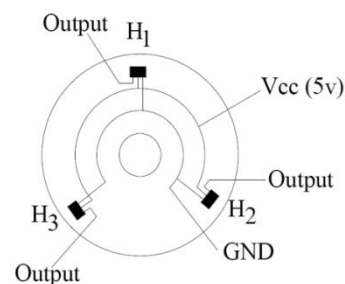
This trainer has digital control along with basic DSP functions like filtering, PWM generation and calculation of spectral characteristics of input analog signals. The TMS320LF2407A contains a C2xx DSP core along with useful peripherals such as ADC, Timer, PWM Generation integrated onto a single piece of silicon. The Micro-2407 trainer can be operated in two modes. In the mode:1(serial mode ) the trainer is configured to communicate with PC through serial port. In the mode: 2 (stand alone mode), the trainer can be interacted rough the IBM PC keyboard and  $16 \times 2$  LCD display.



**Figure 17 Experimental Setup for Speed Control of PMLDLC Motor**

#### 3.2 PMLDLC Hall Sensor

Hall Effect sensor provides the information needed to synchronize the motor excitation with rotor position to produce constant torque. It detects the change in magnetic field. The rotor magnets are used as triggers to the Hall Sensor. A signal conditioning circuit integrated within the Hall switch provides a TTL-compatible pulse with sharp edges. Three Hall Sensors placed  $120^\circ$  apart, are mounted on the stator frame. The Hall Sensor digital signals are used to sense the rotor position. The Hall sensors connection details are shown in Figure 18.



**Figure 18 Hall Sensors Connector Details**

#### 3.3 Switching Sequences

The "x" denotes either 0 or 1 and  $s_1, s_2, s_3, s_4, s_5, s_6$  denotes the switches. The PMLDLC motor is operated in  $120^\circ$  mode of conduction. The Hall sensor output and the position of switches for various positions of rotors are given in Table 5.

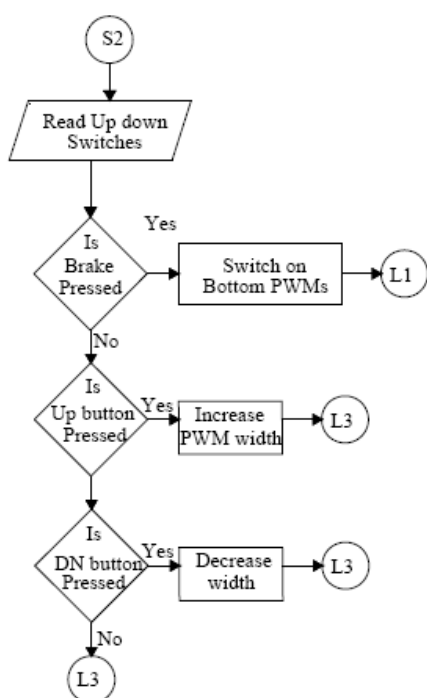
**Table 5 Switching Sequence of MOSFETs and the Hall Sensor Outputs**

Hall Sensor Output			PWM Output						Modes of Operation	Rotation in Degrees
H <sub>1</sub>	H <sub>2</sub>	H <sub>3</sub>	s <sub>1</sub>	s <sub>2</sub>	s <sub>3</sub>	s <sub>4</sub>	s <sub>5</sub>	s <sub>6</sub>		
0	1	0	1	0	0	0	0	1	120°	0°-30°
1	1	0	0	0	1	0	0	1		30°-60°
1	0	0	0	1	1	0	0	0		60°-90°
1	0	1	0	1	0	0	1	0		90°-120°
0	0	1	0	0	0	1	1	0		120°-150°
0	1	1	1	0	0	1	0	0		150°-180°
0	1	0	1	0	0	0	0	1		180°-210°
1	1	0	0	0	1	0	0	1		210°-240°
1	0	0	0	1	1	0	0	0		240°-270°
1	0	1	0	1	1	0	0	0		270°-300°
0	0	1	0	0	0	1	1	0		300°-330°
0	1	1	1	0	0	1	0	0		330°-360°
X	X	X	1	0	1	0	1	0		-

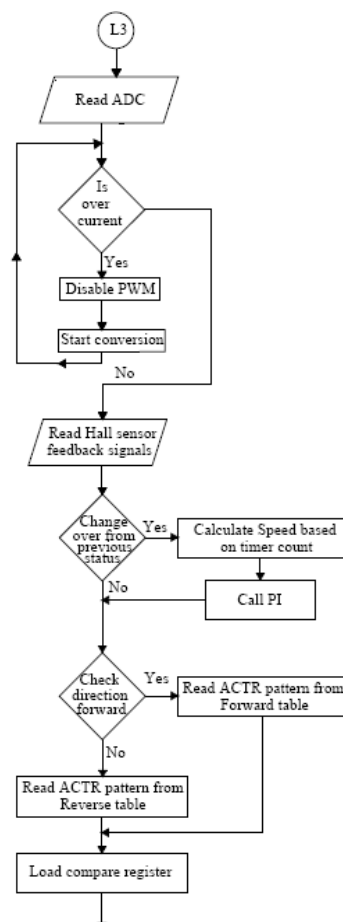


When the rotor lies between  $90^\circ$ - $120^\circ$  the Hall sensors  $H_1$  and  $H_3$  produce the output. The upper switch  $s_5$  is driven in to conduction based on Hall sensor ( $H_1$ ) output and lower switch  $s_2$  is drive in to conduction based on Hall sensor ( $H_3$ ) output. Similarly based on the position of the rotor, the upper switches and lower switches are driven in to conduction. The difference between the rotor speed and reference speed reduces the error. The duty cycle of the switches is controlled by PI controller with respect to error.

Figure 19a shows the flow chart to vary the width of PWM output. Fig 19b shows the flow chart to calculate the speed of motor based on timer count and Hall sensor output.



**Fig 19a Flow Chart to Vary the Width of PWM Output**



**Figure 19b. Flow Chart to Control the Speed of PMSLDC Motor in the Presence of Sensor Using PI Controller Scheme**

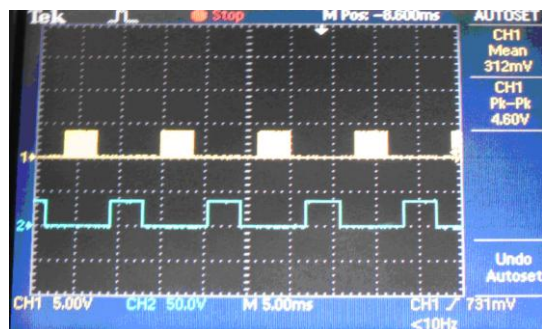
Figure 20 shows the Hall sensor output. Based on the Hall sensor output the switching sequence of the inverter is varied and hence the stator voltage applied to the stator coil varies. The speed of the motor depends on the applied voltage and hence varying the applied voltage the speed can be controlled.



**Figure 20 Hall Sensor Output**

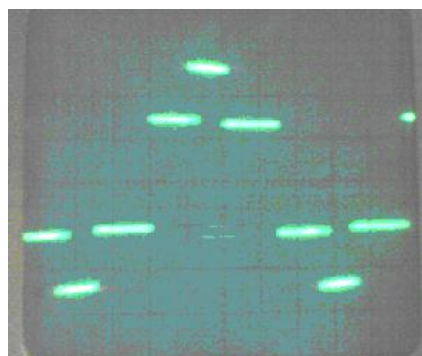
Figure 21 shows the PWM signal applied to the MOSFETs of the inverter. Based on the position of rotor the 3 Hall sensor output varies which is used to identify the position of the switches. The speed of the motor is compared with reference speed and the error is

obtained. The PI controller with error as input varies the duty cycle of PWM signal.



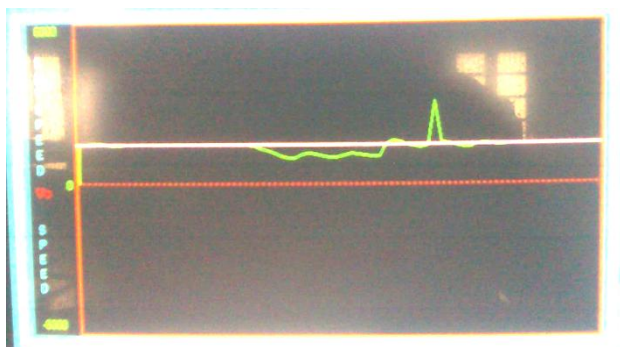
**Figure 21 PWM Signal to the Inverter**

The oscillogram of three phase inverter output voltage is depicted in Figure 22.



**Figure 22 Three Phase Inverter voltage**

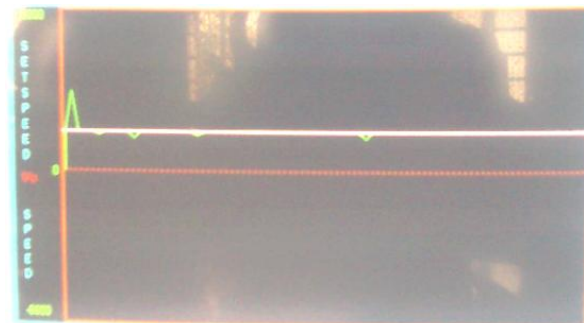
Figure 23 shows the variation of speed with load disturbance. When the motor is running at desired speed load disturbance is applied. The load disturbance is reflected as variation in speed as shown in Figure 23. Due to the PI controller action the speed reaches the desired speed of 1500 rpm after a few second.



**Figure 23 Variation of Speed with Load Disturbance Using PI Controller Scheme (Speed Reference: 1500 rpm)**

Figure 24 shows impact on speed due to the variation in supply voltage. Initially the applied voltage is increased which is reflected as increase in speed as

spike. The output of the PMBLDC motor is compared with reference speed and the error is fed as an input to PI controller. The PI controller reduces the error and the rotor tracks the desired set speed



**Figure 24 Variation of Speed with Supply Voltage using PI Controller Scheme (Speed Reference: 1500 rpm)**

The drawbacks in speed control of PMBLDC motor is embedding the Hall sensors into the stator is a complex process and involves high implementation cost.

## Conclusion

Closed loop controlled Inverter fed PMBLDC motor using PWM control is modelled, simulated and implemented in real time. Feedback signals from the PMBLDC motor representing speed are utilized to get the driving signals for the inverter switches. The simulated results are at par with the real time results. The switching angle for the pulse is selected in such way to reduce the harmonic distortion. The experimental results and simulation results were presented.

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