"A NOVEL TECHNIQUE TO CONTROL THE SPEED OF PM BRUSHLESS DC MOTOR FOR ELECTRIC BIKE"

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the degree of

MASTER OF TECHNOLOGY
IN

ELECTRICAL ENGINEERING

(Power Apparatus & Systems)

By

BHILA DHIREN N.
(05MEE005)

Department of Electrical Engineering
INSTITUTE OF TECHNOLOGY
NIRMA UNIVERSITY OF SCIENCE AND TECHNOLOGY
AHMEDABAD 382 481

MAY 2007

CERTIFICATE

This is to certify that the Major Project Report entitled **"A NOVEL TECHNIQUE TO CONTROL THE SPEED OF PM BRUSHLESS DC MOTOR FOR ELECTRIC BIKE"** submitted by **Mr. BHILA DHIREN N. (05MEE005)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Power Apparatus & Systems of Nirma University of Science and Technology is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

Date:

Industrial - Guide

Mr. Himanshu Swami
Astt. Manager R&D,HEV
Electrotherm India Pvt.Ltd.
AHMEDABAD

Institute - Guide

Dr. P.R.Upadhyay (A.P.E.E.)
Dept. of Electrical Engg.
Institute of Technology NUST
AHMEDABAD

Head of Department
Department of Electrical Engineering
Institute of Technology
Nirma University
Ahmedabad

Director
Institute of Technology
Nirma University
Ahmedabad

Acknowledgement

I am thankful to my industrial guide Mr. HIMANSHU SWAMI for providing me his continuous support and guidance throughout the project. I am grateful to him for providing me enough impedance and flexibility as I struggled with problems and explored any number of ideas to solve them. I consider myself very fortunate to have worked with him. It was amazing to see the skill he displayed in solving the problems while performing the experiment and for providing me his support in getting the results. I want to express my sincere thanks to Mr. PRIYANG DOSHI for his guidance, encouragement, excellent support during my project work.

I am also thankful to my institutional guide Dr. P.R. UPADHYAY, presently working as a professor in Nirma University of Science and Technology for providing his continuous support and encouragement till the end.

I am also thankful to ELECTROTHERM INDIA PVT.LTD. A wonderful place with excellent facilities to work and explore to learn and interact plays its role in my dissertation. My sincere thank to industrial staff members, Mr. PRADIP SAVALIYA, Mr. NANDISH BHAI & Mr. PRIYANK BATERIWALA for giving me supports during my project. I am heartly thankful to Mr. VIMAL AMRUTIYA for providing me computer facility for my dissertation work and finally, I am also thankful to institutional staff members for providing me, Simulation tool & laboratory facilities during my project work.

My family provided me constant support & kept up my spirits till the end of project.

Abstract

The work presented in this thesis deals with the simulation, design & development of the buck converter fed PM Brushless DC Drive. Speed of the motor is controlled by varying the D.C. Link voltage of the three phase inverter. Buck converter is used to vary the D.C. Link voltage of the inverter. By varying the duty cycle of the buck converter, output voltage of the buck converter is varied & consequently the speed of the motor is controlled. Simulation of the buck converter & PM Brushless DC Drive is carried out in the PSIM simulation tool.

Pulses of the buck converter are generated by comparing triangular wave with that of the signal coming from the accelerator of the bike, which is the variable d.c. voltage. Buck converter is designed with the voltage & current ripples of 1%. Switching frequency considered in this work for the buck converter is 20 kHz.

The simulation results of the 3-phase inverter are validated using resistive load as well as the driven motor. For the resistive load, three 120° phase shifted pulses are obtained from three phase transformer. Then these three sine waves are converted into square waves. Dead time between the pulses of the same phase MOSFETs is generated by triggering the Monostable Multivibrator on the positive edge of the input pulses & then by EX-ORING the triggering pulses with the positive edge triggered pulse. Driver I.C. being used for MOSFET is the IR 2110. MOSFETs being used are IRFP 240.

Motor is first driven manually & observed the Hall-effect sensors signals, which are 120’ phase shifted. Opto coupler is used to invert the three output signals obtained from the Hall Effect sensors & finally 6-output signals are obtained. To remove the loading of the opto coupler on the Hall-effect sensor signals, Buffer I.C. 4050BC is used. Motor is driven on No-load & speed of the motor obtained at 90% duty cycle. The obtained maximum speed is 340 rpm. Speed is controlled from 200 rpm to 340 rpm by varying duty cycle between 60% to 90%.

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Chapter 1

INTRODUCTION

1.1 General

With ever increasing concern on energy efficiency, efficiency diversification & environmental protection the development of electric vehicle (EV) technology has taken on an accelerated pace.

The actual revival of EVs should be due to the ever increasing concerns on energy conservations & environmental protection:

- EV offer high energy efficiency. In general, the overall energy conversion efficiencies from crude oil to vehicle motion for EVs and gasoline-powered vehicle are 12.5% and 9.3%, respectively.
- EVs allow energy diversification. Electricity can be generated not only from thermal power using oil & coal, but also from hydro power, wind power, geothermal power, wave/tidal power, solar power & nuclear power.
- EVs are vibration-free & less noisy compared to gasoline-powered vehicles.

Basic requirement for EVs is a portable source of electrical energy. With available choice of portable energy sources, batteries have been the most popular choice of energy source for EV. But this has a limited travel range capability [1].

1.2. Block- diagram of the buck converter fed PM BLDC Drive.

The basic schematic of a buck converter fed PM BLDC drive is shown in fig.1. Speed of the brushless D.C.Motor can be changed by, controlling the D.C.link voltage of the inverter. In case of the electric vehicle, the signal from accelerator will decide the duty cycle of the device used in buck-converter. By varying the duty cycle of the switch used in buck-converter, the d.c.link voltage of the inverter can be varied and consequently the speed of the motor can be controlled.

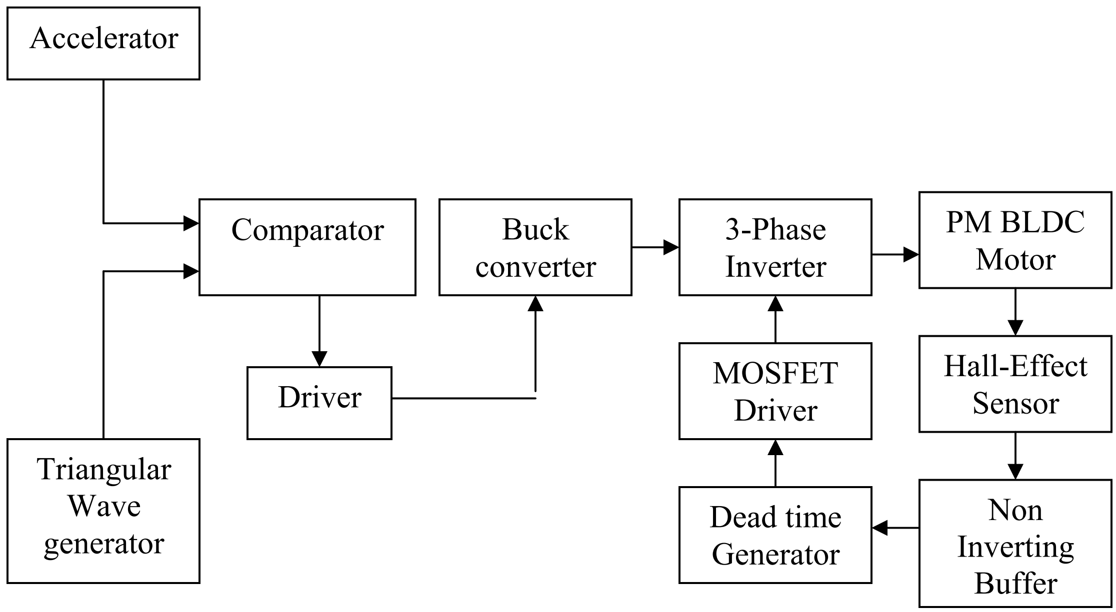

Fig.1 Block diagram of the buck converter fed PM BLDC Drive

The Switching frequency of the inverter is to be decided by the Hall sensor Signals. Of course the switching frequency of the inverter is lower, so definitely lower the switching losses. Inverter is to be operated by square wave pulses, resulting the lesser torque ripple.

1.3 Introduction to EV

Electric vehicle that utilizes chemical energy stored in rechargeable battery packs. Electric vehicles use electric motors instead of, or in addition to, internal combustion engines (ICEs). Vehicles using both, electric motors and ICEs, are examples of a hybrid vehicles.EVs are usually automobiles, light trucks, motorized bicycles, electric scooters, golf carts, forklifts and similar vehicles, because batteries are less appropriate for larger long-range applications. EVs were among the earliest automobiles, and are more energy-efficient than all internal combustion vehicles.EVs produce no exhaust fumes, and minimal pollution if charged from most forms of renewable energy. Many are capable of acceleration exceeding that of conventional gasoline powered vehicles.EVs reduce dependence on petroleum, may mitigate global warming by alleviating the greenhouse effect, are quieter than internal combustion vehicles, and do not produce noxious fumes.

1.4 Advantages of electric vehicles

Electric motors are used to drive vehicles because they can be finely controlled, they deliver power efficiently and they are mechanically very simple. Electric motors often achieve 90% conversion efficiency over the full range of speeds and power output and can be precisely controlled. Electric motors can provide high torque while an EV is stopped, unlike internal combustion engines, and do not need gears to match power curves. This removes the need for gearboxes and torque converters. Electric motors also have the ability to convert movement energy back into electricity, through regenerative braking. This can be used to reduce the wear on brake systems and reduce the total energy requirement of a trip.

Another advantage is that electric vehicles lack the vibration and noise pollution of a vehicle powered by an internal combustion engine. Trolleybuses are especially capable of this advantage, due to the fact that trolleybuses also lack the noise of steel wheels on rails, unlike Trams[2].

1.5. Literature review

(1) Byeong-seok Lee & R. Krishnan

"A Variable Voltage Converter Topology for Permanent-Magnet Brushless DC Motor Drives using Buck-Boost Front-End Power Stage"

A variant of a low cost, four-quadrant converter topology for permanent magnet brushless DC (PMBDC) motor drives is proposed in this paper. It has the advantage of variable dc input voltage to the machine through a buck-boost front-end power stage and hence low torque ripple at very low speeds, a desirable feature in high performance applications. It has the fixed commutation voltage, which is equal to the dc source voltage. The machine dc link voltage can be varied from zero to twice the dc source voltage through the step-down and step-up operation of buck boost front-end chopper power stage. In low speed operational range, small dc link voltage is sufficient for the phase current control due to low back emf generated. For this reason, lower switching ripple and hence lower torque ripple can be obtained by step-down operation of the buck-boost front-end converter. It uses the half control technique for the inverter.

(2) Tay Siang Hui, K.P. Basu & V. Subbiah

"Permanent Magnet Brushless Motor Control Techniques"

In this paper various control techniques are given to control the speed of the motor. Author has gone through various control techniques like, commutation control method, speed control method, starting control method, position detection method, performance control method. In commutation control method, various methods are available like, half control, 120º control, 180º control. Among these control techniques, 180º control method provides the best result because of any one instant, all three phases are active, which means that there is 100% copper utilization. For the speed control, two techniques are available. One is by varying DC bus rail voltage with the constant PWM duty cycle & other is by varying PWM duty cycle. Starting control method is necessary to know the initial rotor position of the motor. By turning on the two switches on the lower side of IGBT & by applying PWM on one of the high side switch in an incremental mode. This aligns the rotor in the middle of two switching position. Than the author has gone through position sensing method, performance control, & torque control method. In Torque control method, open loop control & closed loop control technique is explained for compressor load.

(3) Victor M., Cardenas G., Sergio Horta M., Rodolfo Echavarria S.

"Elimination of Dead Time Effects in Three Phase Inverters".

In this paper, an analysis & compensation of the dead time effects in three phase inverters is presented. Dead time generates a decrease in the magnitude voltage of the harmonic fundamental & an increase in the low order harmonics. If dead time is not compensated, rms voltage of the fundamental harmonic becomes lower. This lower value causes a reduction in the motor torque. Compensation of the dead time effects is done by shifting the positive edge of the pulse by +tm factor. Which means +tm factor is added in the dead time. It can be appreciated that by factor 1/n the deviation will be higher in the low order harmonics. Which means that as the order of harmonics is lower, increase in the magnitude voltage of the harmonic fundamental.

(4) R.Krishnan & P. Vijayraghavan

"A new power converter topology for PM Brushless DC Motor drives"

A new converter topology for permanent magnet brushless DC Motor is proposed in this paper. Advantages of this topology are lower torque ripples & switching ripples at low speed. Also only three switches & diodes are needed to implement this topology. Speed of the motor is controlled by varying the duty cycle of the buck converter.

1.6 Components of electric bike

Main components of the electric bike are:

1. Battery.
2. Electric motor
3. Power converter & controller

Following sections give details of above components.

1.6.1. Battery

Battery specifications: 12V, 20Ahr/20hr sealed lead-acid 4 in series. Lead-acid batteries are preferred over other batteries for bikes. These batteries are extensively used due to following:

- Relatively low cost.
- Easy availability of raw materials(lead sulfur)
- Ease of manufacture.
- Safe & reliable.

1.6.2. Electric Motor

The electric motor for use on an electric bike should be small in size and should have a high efficiency. Due to space limitations, the motor have a short axial length. The electric motor for use on an electric bike must fulfill the following requirements.

- EV motors need to offer the maximum torque that is four to five times of the rated torque for temporary acceleration & hill-climbing.
- EV motors need to achieve four to five times the base speed for highway cruising.
- EV motors should be designed according to the vehicle driving profiles & drivers habits.
- EV motors demand both high power density and good efficiency map (high efficiency over wide speed & torque ranges) for the reduction of total vehicle weight & the extension of driving range.
- EV motors desire high controllability, high steady state accuracy & good dynamic performance for multiple-motor coordination.
- EV motors need to be installed in mobile vehicles with harsh operating conditions such as high temperature, bad weather, & frequent vibration.

1.6.2.1. Classification of EV motors

Those motors applicable to electric propulsion can be classified as two main groups, namely the commutator motors & commutatorless motors. Fig.2 denotes the classification of EV motors.

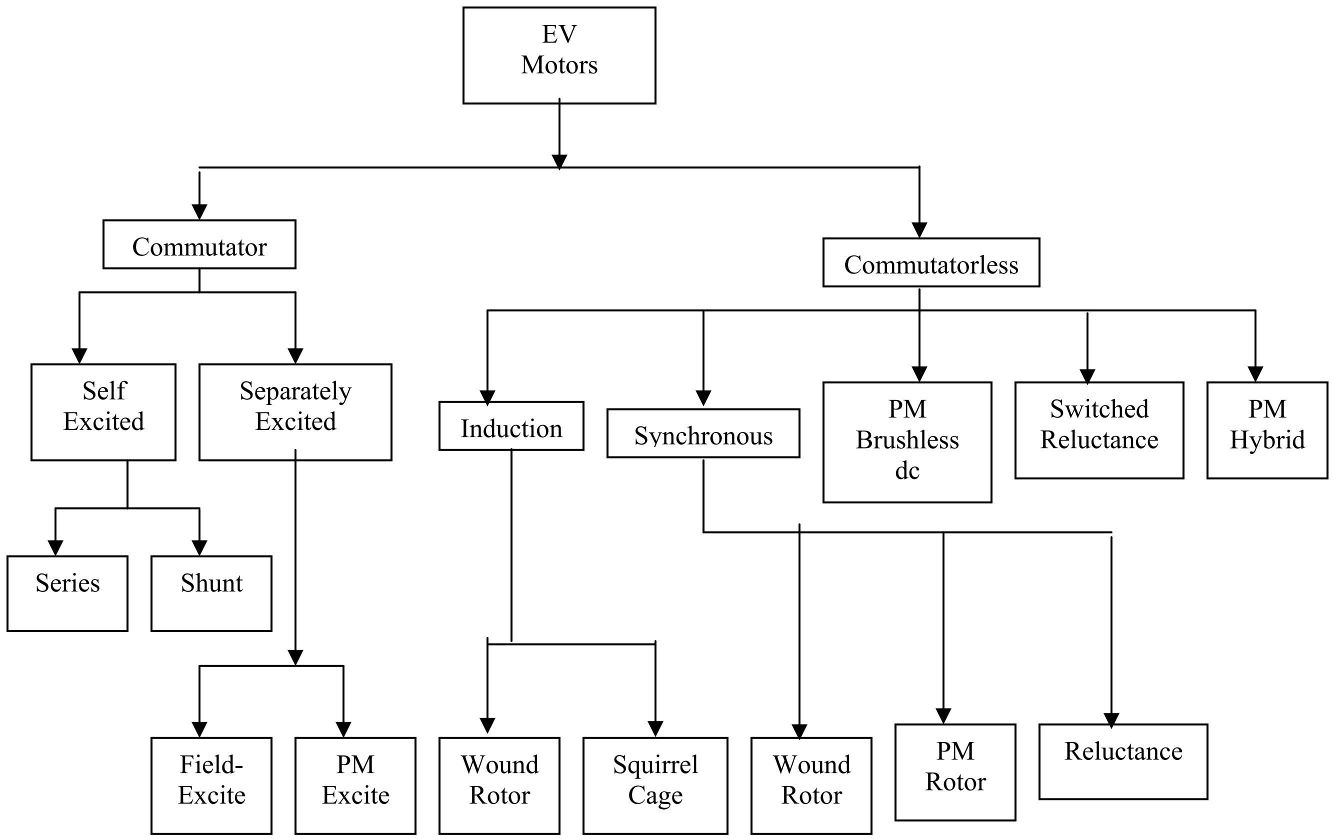

Fig.2 Classification of EV motor

1.6.2.2. Evaluation of EV motors

Table.1 Evaluation of EV Motors

	DC Motor	Induction Motor	PM Brushless DC Motor	SR Motor	PM hybrid Motor
Power density	2.5	3.5	5	3.5	4
Efficiency	2.5	3.5	5	3.5	5
Controllability	5	4	4	3	4
Reliability	3	5	4	5	4
Maturity	5	5	4	4	3
Cost	4	5	3	4	3
Total	22	26	25	23	23

In order to evaluate the aforementioned EV Motor types, a point grading system is adopted. The grading system consists if six major characteristics and each of them is graded from 1 to 5 points, As listed in table 1.This evaluation indicates that induction motors are relatively most acceptable. When the cost & maturity of PM Brushless (including ac or dc) motors have significant improvements, these motors will be most attractive. Conventional dc motors seem to be losing their competitive edges, whereas both SR & PM hybrid motors have increasing potential for EV propulsion

By replacing the field winding of dc motors with PMs, PM dc motors permit a considerable reduction in stator diameter due to efficient use of radial space. Owing to low permeability of PMs, armature reaction is usually reduced & commutation is improved. Due to these advantages, PM Brushless DC motors are the most preferable motors in EVs [3].

1.6.3. Power converter & controller/Motor Drive

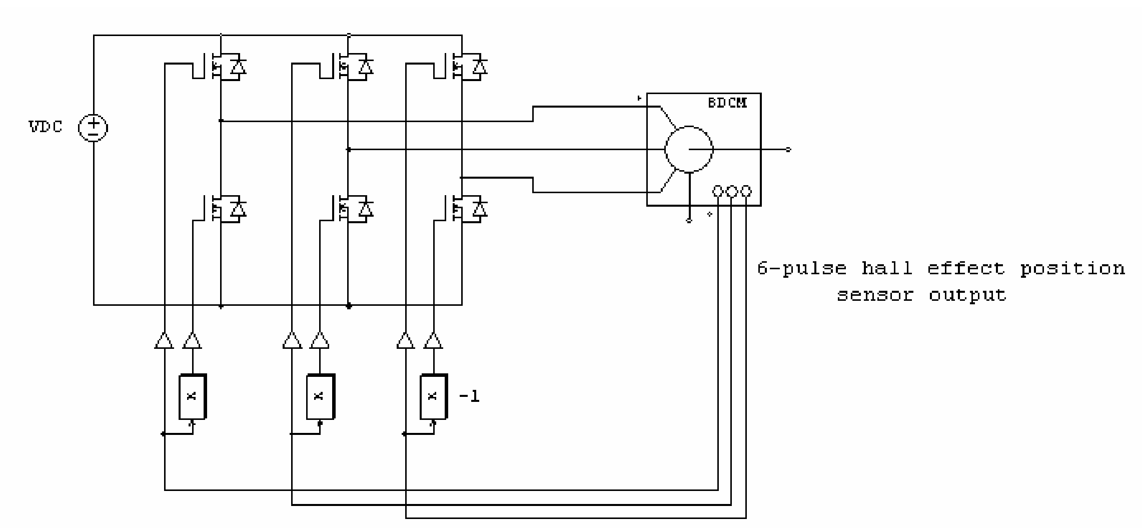

Fig.3 Power converter for PM BLDC Drive

Power converter is an important part of the PM BLDC drive. Function of the power converter is to convert fixed supply voltage into variable voltage & variable frequency supply. For this purpose, switching devices are used in the power converter like BJT, MOSFET, IGBT, SCR, GTO, & MCT. Selection of the switching device should be done according to the needed switching frequency, & current requirement of the load. BLDC is a permanent magnet DC Machine. Unlike DC Motor, BLDC motor requires electronics commutation. Fig.3 shows the block diagram of a simple BLDC drive. Three phase output of the inverter is given to the BLDC motor. To rotate the motor, stator has to be excited in the proper sequence. Hall Effect sensors are used to sense position of the motor. Signals obtained from the Hall Effect sensor are used to excite the proper phase of the motor, by switching of the MOSFETs.

1.7. Control strategies

There are various control strategies are available to control the speed of the BLDC Motor. One of them is pulse amplitude modulation, & other is pulse width modulation.

1.7.1. Pulse amplitude modulation

In this strategy, speed of the motor can be controlled by varying the D.C. Link voltage of the inverter. For this purpose, buck-boost converters are employed. This strategy is quite simple & efficient than pulse width modulation. Two control techniques can be employed for switching of the device. One is 180° control & other is 120° control. In 180° control scheme, each switch remains on for an angular duration of 180° electrical in one complete rotation, while in 120° control, each switch remains on for an angular duration of 120° electrical in one complete rotation [4].

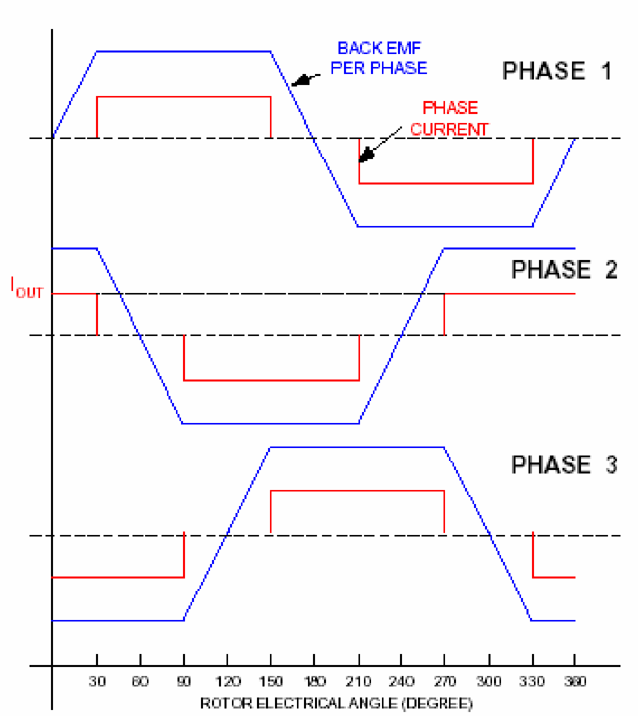

Fig.4 Pulse amplitude modulation strategy

1.7.2. Pulse width modulation

1.7.2.1 Half control

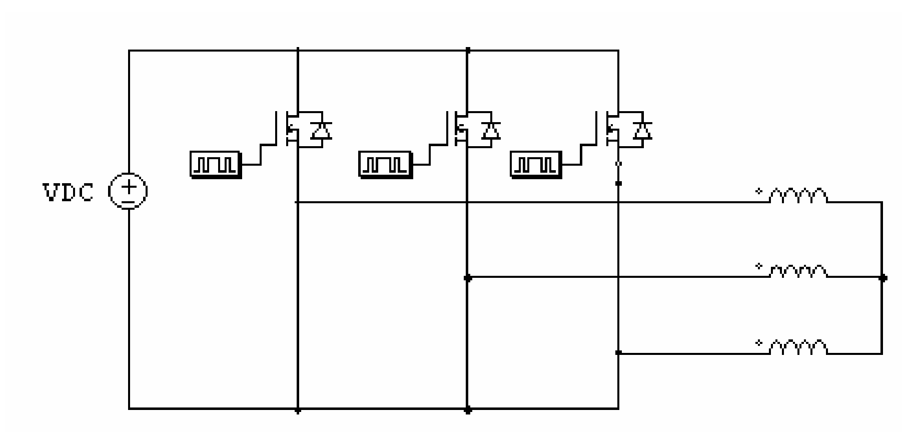

Fig.5 Half control strategy

In half control only three switches are used as either high side switches or low side switches for speed control. As in fig.5. This method is quite simple but efficiency of the motor is low. Further more, the pulsation of torque is very high as the step size is reduced.

1.7.2.2. 120º control

In 120° control, any time two phases of the motor are energized. At a time two switches conduct & after every 60°, one of the two conducting switches changes its state. This control strategy is more efficient than 60° control, and pulsation of torque is lower than the half control strategy. Table 2. Shows the switching sequence of the 120° control.

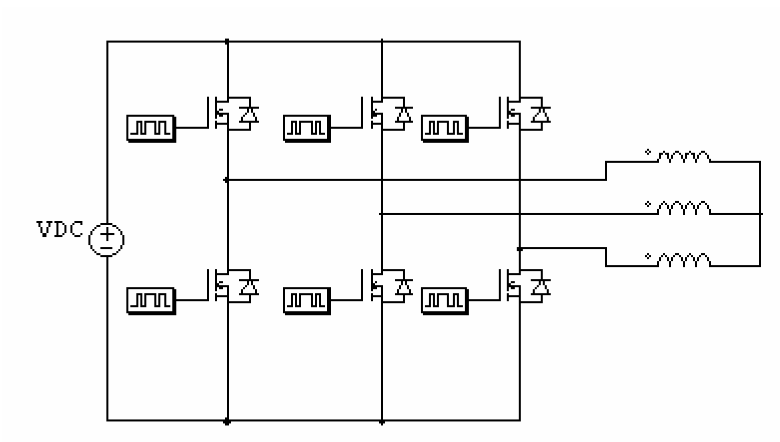

Fig.6 Control strategy of the inverter

Table.2 Switching Sequence of 120º Control scheme

	Up	Vp	Wp	Un	Vn	Wn
1	On	Off	Off	Off	On	Off
2	On	Off	Off	Off	Off	On
3	Off	On	Off	Off	Off	On
4	Off	On	Off	On	Off	Off
5	Off	Off	On	On	Off	Off
6	Off	Off	On	Off	On	Off

1.7.2.3. 180° control

This control strategy is most efficient strategy among all three control strategy. In 180° control, three switches conduct at a time & consequently, all the three of the stator winding is energized. Table 3. Shows the switching sequence of the 180° control. Because of at any one instant all three of the phases are active, utilization of copper becomes 100%. Dead time must be inserted between two same phase switches to stop simultaneous conduction of the two switches. In 180° control, pulsation of torque is minimum compare to above two techniques [5].

Table.3 Switching Sequence of 180° Control scheme

	Up	**Vp**	**Wp**	**Un**	**Vn**	**Wn**
1	On	Off	Off	Off	On	On
2	On	Off	On	Off	On	Off
3	Off	Off	On	On	On	Off
4	Off	On	On	On	Off	Off
5	Off	On	Off	On	Off	On
6	On	On	Off	Off	Off	On

1.8 Organization of the report

The overview of the report is as follows

In **chapter 1** introduction to EVs is given. Components of electric bike are mentioned. Classification & evaluation of EV Motors & various strategies to control the speed of the BLDC Motor are explained. In **chapter 2** backgrounds and principle of BLDC drive is explained. In **chapter 3** introduction, design & simulation of the buck converter for various duty cycles are given. In **chapter 4** introductions of the three phase inverter, 180° control & simulation of the buck converter fed BLDC drive is given for No-load & constant torque load. **Chapter 5** covers the Development of buck converter fed PM BLDC Drive to control the speed of the BLDC Motor, which includes the buck converter, control circuit, & power circuit of the three phase inverter. Results are given for the inverter, driven on the resistive load & motor load.

1.9 Conclusions

Electric vehicle reduce the dependence on petroleum, may mitigate global warming by alleviating the green house effect, are quieter than internal combustion vehicles and do not produce noxious fumes. Motors used to drive electric vehicles, can be finely controlled, they can deliver power efficiently. Also can provide high torque while EV is stopped, unlike internal combustion engines, and do not need gears to match power curves. This removes the need for gear boxes and torque converters. Motors also have the ability to convert movement energy back into electricity, through regenerative breaking. This can be used to reduce the wear on brake systems & reduce the total energy requirement of a trip. Brushless DC Motors is the most promising candidate for EV. Applications among all the motors, because of high efficiency, compactness, ease of control, ease of cooling, low maintenance & low noise emission. Among all the control techniques, 180º control is the most efficient technique, because of at a time three switches conducts & due to that 100% copper utilization is there. Moreover, pulsation of the torque is the minimum in this technique.

Selection of the control technique of 180° control is to be done from the literature 2. A new technique of Buck converter fed PM BLDC Drive is developed from the literature 1 & 4, where half control technique is implemented. While this theses deal with the 180° control technique for inverter. Elimination of the dead time effect in three phase inverter can be implemented as the scope for the further work.

Chapter 2

PM BRUSHLESS DC MOTOR

2.1 Historical development of PM BLDC Motor

In the BLDC Motor, field winding is on the rotor & armature winding is on the stator. In BLDC Motor, brushes are eliminated & electronics commutation is used. Due to this efficiency of the motor is higher compare to DC Motor. Field of the motor is made of permanent magnet & due to that the energy density of the motor is higher & inertia of the motor can be compressed. In BLDC Motor, winding of the motor is concentrated, generated emf is trapezoidal nature. The flat constant portion of the back emf should be 120 º portions for the smooth torque production. To rotate the motor, stator winding of the motor should be excited in a proper sequence. In order to understand the sequence of the stator winding to energize, rotor position of the motor should be sensed. Hall Effect sensors are used to sense the position of the rotor. Output of the Hall Effect sensors is a logic signal. This logic signal is used for switching of the switches in the inverter. Hall Effect sensors are embedded either on the stator or in the rotor of the motor.

2.2. Principle of a BLDC Drive

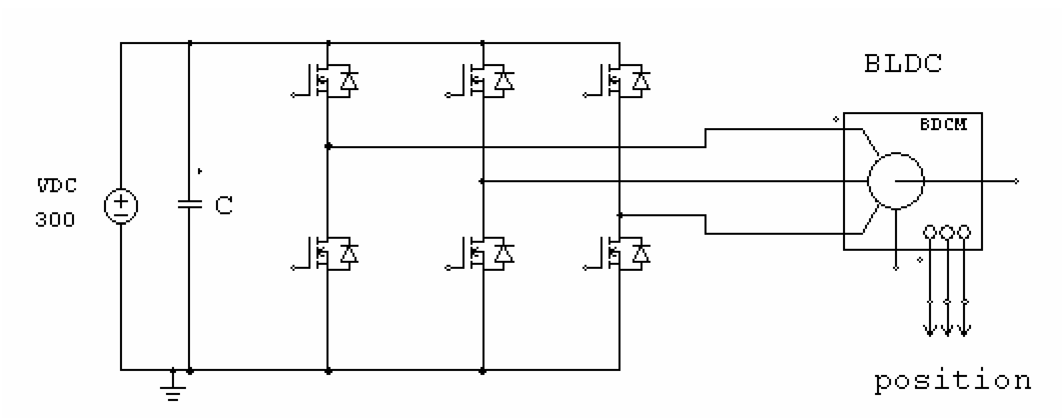

Fig.7 Voltage source inverter fed BLDC Drive

VSI (Voltage source inverter) or CSI (Current source inverter) is used to supply the currents in the stator winding of the motor. In a VSI, 120 º control and 180º control scheme is used. In a 180º control, three switches conduct at a time & in 120º control, two switches conduct at a time. T1, T3, T5 are the high side switches & T2, T4, T6 are the low side switches. When T1, T3, T5 conducts, current enters in the motor winding & current leaves the motor with the conduction of the low side switches. As shown in fig.8 there is a definite relation between back emf & current waveform of the motor. In order to rotate motor properly, synchronization of the emf waveform & current waveform is necessary. Hall Effect sensor maintains this synchronization of the emf & current waveforms.

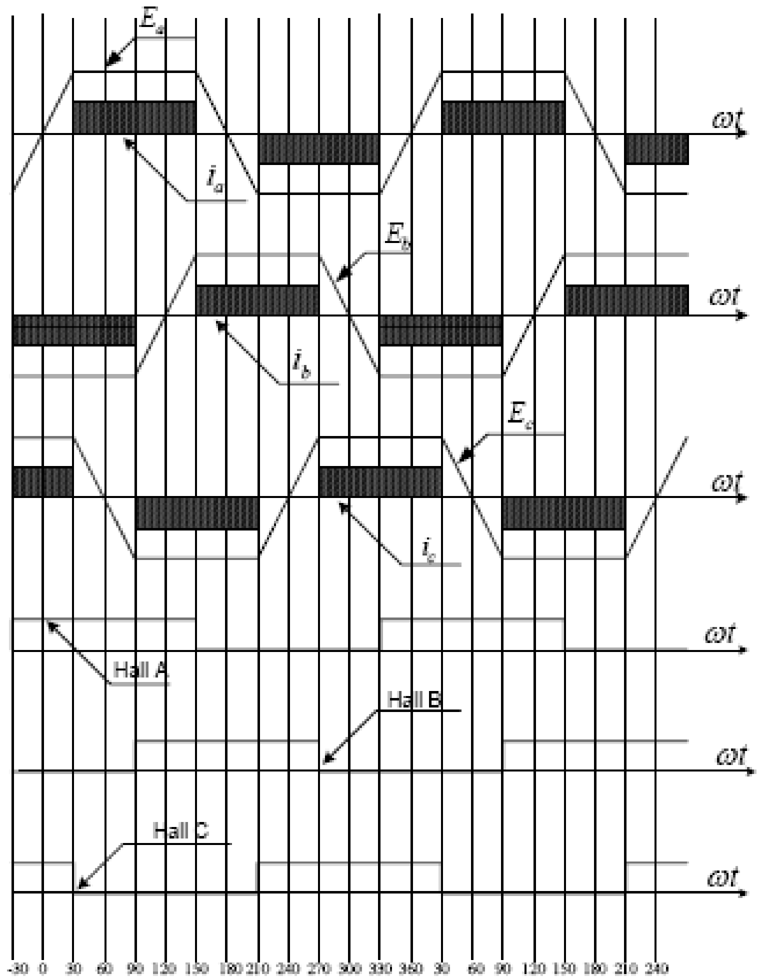

Fig.8 Back-emfs, current waveforms and Hall position sensors for a BLDC

The rising and falling pulse edges of the Hall position sensors are used as triggers for timing circuits used in the control algorithm [6].

2.3. Torque/speed characteristics of PM brushless DC Motor

Figure 9. Shows the torque/speed characteristics. There are two torque parameters used to define a BLDC motor, peak torque (TP) and rated torque (TR). During continuous operations, the motor can be loaded up to the rated torque. The torque remains constant for a speed range up to the rated speed. The motor can be run up to the maximum speed, which can be up to 150% of the rated speed, but the torque starts dropping. Applications that have frequent starts and stops and frequent reversals of rotation with load on the motor, demand more torque than the rated torque. This requirement comes for a brief period, especially when the motor starts from a standstill and during acceleration. During this period, extra torque is required to overcome the inertia of the load and the rotor itself. The motor can deliver a higher torque, maximum up to peak torque, as long as it follows the speed torque curve [7].

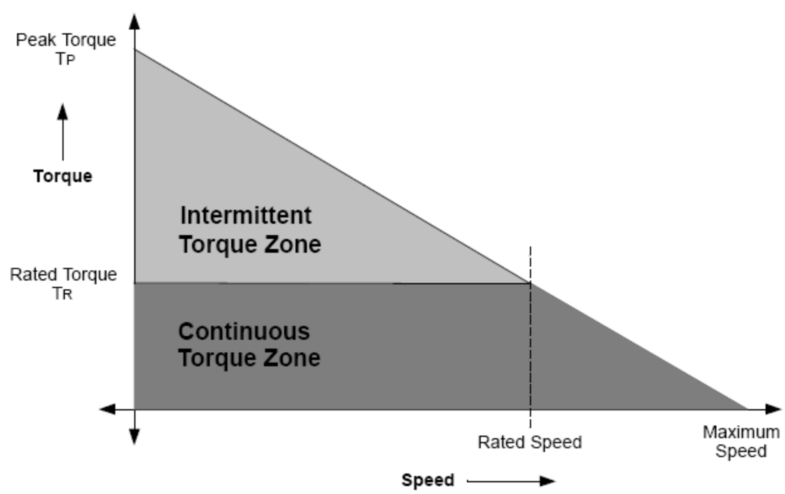

Fig.9 Torque/speed characteristics of PM BLDC Motor

2.4. Conclusions

PM Brushless DC Motors have advantages over brushed dc motors & induction motors. They have better speed V/S torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges, rugged construction.

Also torque deliver to motor size is higher, making it useful in applications where space & weight are critical factors. With these advantages, BLDC Motor find wide spread applications in automotive, aerospace, appliance, consumer, medical, instrumentation, & automobile industries.

Chapter 3

BUCK CONVERTER

3.1 Necessity of dc-dc converter

There exists a need for changing a given value of a dc voltage supply to a desired value. This can be achieved by the use of a Linear Regulated Supply, typically used for supplying Integrated Circuits and other applications where the power supplied is relatively less as compared to motor drives. The disadvantages of a Linear Regulated Supply are that the output voltage is invariably less than the input supply voltage, and since the main output supply transistor operates in the linear region, there is a great deal of power loss (as heat dissipation) associated with this arrangement, thereby leading to a poor efficiency. Dc-dc converters satisfy the need for converting a given dc voltage to a desired dc voltage at relatively high efficiencies. “Buck” converters step down the input supply voltage [8].

Speed of the PM Brushless DC Motor is controlled by varying the D.C. Link voltage of the inverter. Buck converter is used to step down the d.c.link voltage of the inverter.

3.2. Introduction

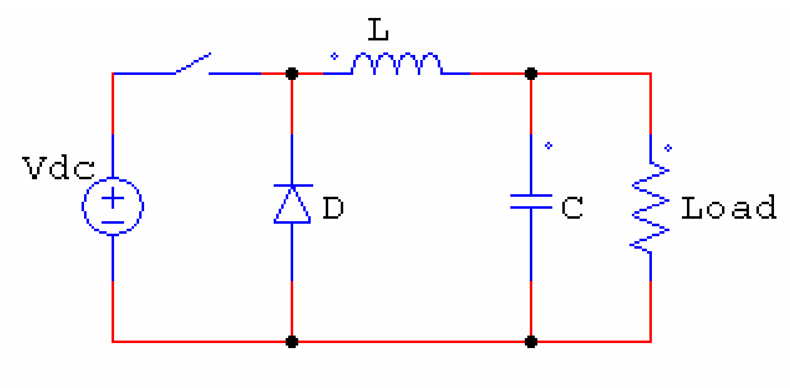

Fig.10 Circuit diagram of Buck converter

Buck converter is a device that accepts a d.c.input voltage & produces a d.c.output voltage. Typically the output produced is at a different voltage level than the input. Buck converter is a d.c. to d.c. converter that steps down the d.c.voltage from its fixed high level to a desired low level. It is also called the forward converter & its circuit topology is shown in fig.10.

Switch is usually an electronic device that operates either in the conduction mode (On) or the cut off mode (Off).The on and off time-periods are controlled by the suitably designed gating circuits, which are usually not shown. The on time of the switch is a fraction of its time period T such that T_{ON} =DT, where D is the duty cycle. During the off time, T_{OFF} = (1-D)T, the freewheeling diode FWD provides a path to maintain the continuity of the current through the inductor. The inductor controls the percent of the ripple and determines whether or not the circuit is operating in the continuous mode. The capacitor C provides the filtering action by providing a path for the harmonic currents away from the load. In addition, its value is large enough so that voltage ripple is very small [9].

3.3. Design of the Buck converter

Buck converter is designed with the input DC Voltage of 36 volt, duty cycle of 90%, switching frequency of the MOSFET is 20 kHz. Voltage & current ripples allowed are 1%.

Design steps:

$$Dutycycle, D = \frac{V_{OUTPUT}}{V_{INPUT}}$$

Where, input voltage of the buck converter is 36 volt, & duty cycle is 90%.

$$0.9 = \frac{V_{OUTPUT}}{36V}$$

$$V_{OUTPUT} = 0.9 \times 36$$

$V_{OUTPUT} = 32.4V$

Thus obtained output voltage from the buck converter is 32.4 volt for duty cycle of 90%.

Time period,

$$T = \frac{1}{frequency} = \frac{1}{20000} = 50\mu S$$

ON Time of the MOSFET is,

$T_{ON} = D \times T = 0.9 \times 50\ \mu S = 45\ \mu S$

OFF Time is,

$T_{OFF} = (1-D) \times T = 0.1 \times 50 = 5\ \mu S$

Equivalent load Resistance,

$$R = \frac{(V_{OUTPUT})^2}{P} = \frac{34.2^2}{250} = 5\Omega$$

Where,

P= Power rating of the motor.

Inductor

Selection of inductor is done by allowing current ripple of 1%,

$$L = \frac{100(1-D)R}{_{\%}CR \times f}$$

Where,

$_{\%}CR$ is the allowed current ripple in the output of the buck converter, which is 1%

$$L = \frac{100(1-0.9)5}{1 \times 20000}$$

L =2.09mH

Thus obtained value of the inductor for current ripple of 1% is 2.09mH.

Average Current through inductor,

$$I_{d.c.} = \frac{V_{OUTPUT}}{R} = \frac{32.4}{5} = 6.48amp.$$

The peak-to-peak current ripple is,

$$I(Peak - peak) = \Delta iL = V_{(OUTPUT)} \times (1-D) \times \frac{T}{L}$$

$$= 32.4 \times 0.1 \times \frac{50 \mu S}{2.09 mH}$$

ΔiL= 0.07 amp.

Maximum current flowing through inductor is,

$$I_{L,MAX} = I_{d.c}. + \frac{\Delta iL}{2}$$

$$= 6.48 + \frac{0.07}{2}$$

= 6.51 amp.

Minimum current flowing through inductor is,

$$I_{L,MIN} = I_{d.c} - \frac{\Delta iL}{2}$$

$$= 6.48 - \frac{0.07}{2}$$

= 6.44 amp.

Which shows that current flowing through inductor is continuous & varies between 6.44 amp. to 6.51 amp.

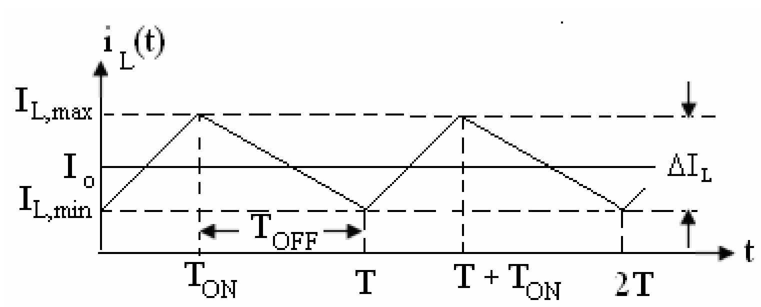

Fig.11 Inductor current of buck converter

CAPACITOR -

Selection of the capacitor done based upon the desired voltage ripple of 1%.

$$C = \frac{(1-D)}{8 \times L \times \left(\frac{\Delta_{VO}}{V_0}\right) \times f^2}$$

$$= \frac{0.1}{8 \times 2.09mH \times 0.01 \times (20000)^2}$$

= 1.5μF, 100V

Where,

$\left(\frac{\Delta_{VO}}{V_0}\right)$ = allowed voltage ripple = 1%

When load current is subtracted from the inductor current, time varying current through capacitor is obtained. It's minimum & maximum values are,

$$I_{C,MAX} = \frac{\Delta iL}{2} = \frac{0.07}{2} = 0.035 amp.$$

$$I_{C,MIN} = -\frac{\Delta iL}{2} = -\frac{0.07}{2} = -0.035 amp.$$

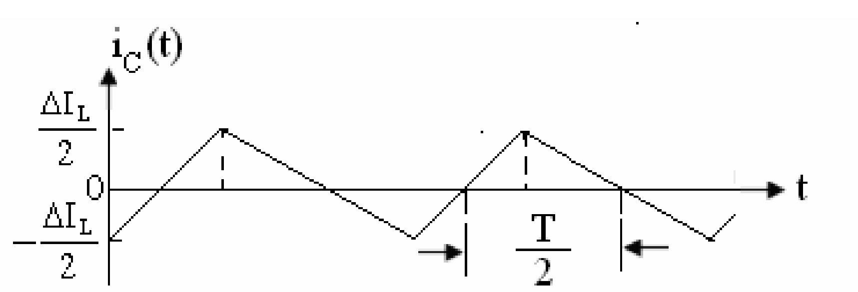

Fig.12 Capacitor current of buck converter

DIODE:

Average current flowing through freewheeling diode,

$I_D = (1\text{-}D) \times I_{d.c.}$

$= 0.1 \times 6.48$

$= 0.648$ Amp.

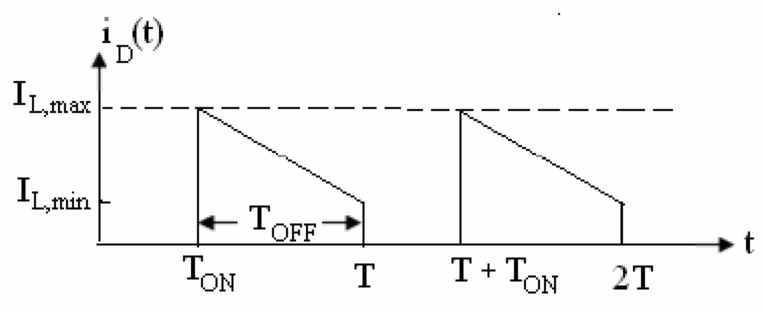

Fig.13 Freewheeling diode current of buck converter

3.4. Simulation of buck converter

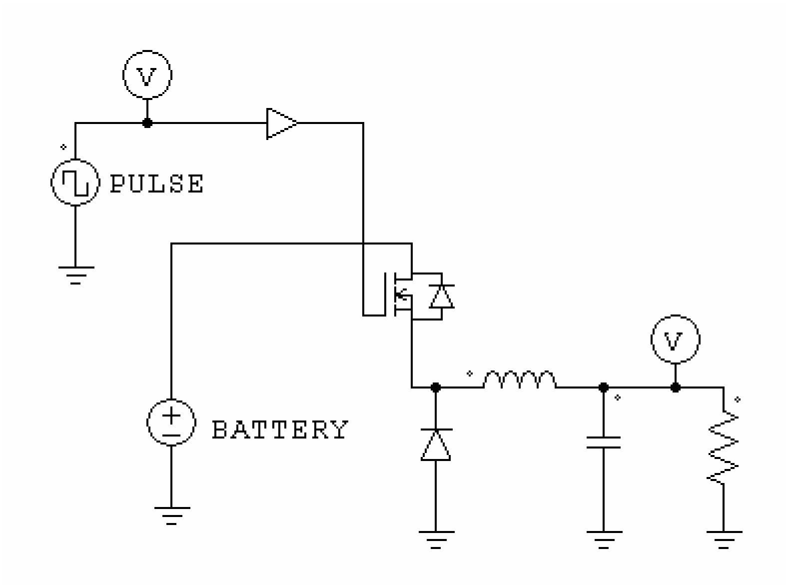

Fig.14 Buck converter used for simulation

Simulation of the Buck converter is carried out in PSIM Simulation tool. By varying the duty cycle of the MOSFET switch, various output voltages are obtained. Ripples obtained in the output voltage are 1%.

3.4.1. Simulation of buck converter for duty cycle of 90%

Voltage obtained in the output of the buck converter is 32 volt as shown in the waveform of the fig.15. Inductor current is continuous & varies from 6.44amp to 6.51 amp as per the design of the buck converter. Fig.16 shows the ripple obtained in the output voltage waveform. Value of the output voltage ripple is nearly 1.5%. This is almost equal to the Design calculation of the buck converter of 1%.

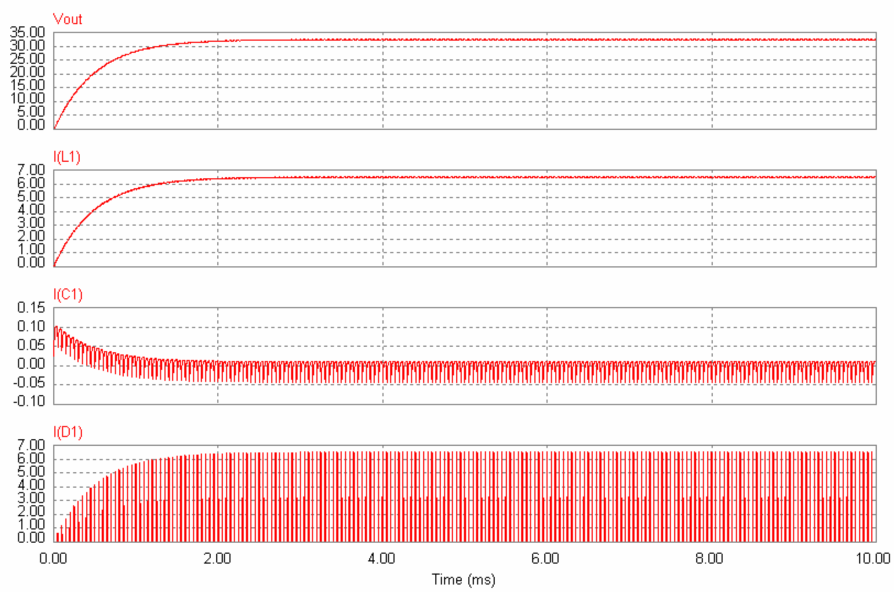

Fig.15 Output voltage, inductor current, capacitor current, and diode current for 90% duty cycle of buck Converter

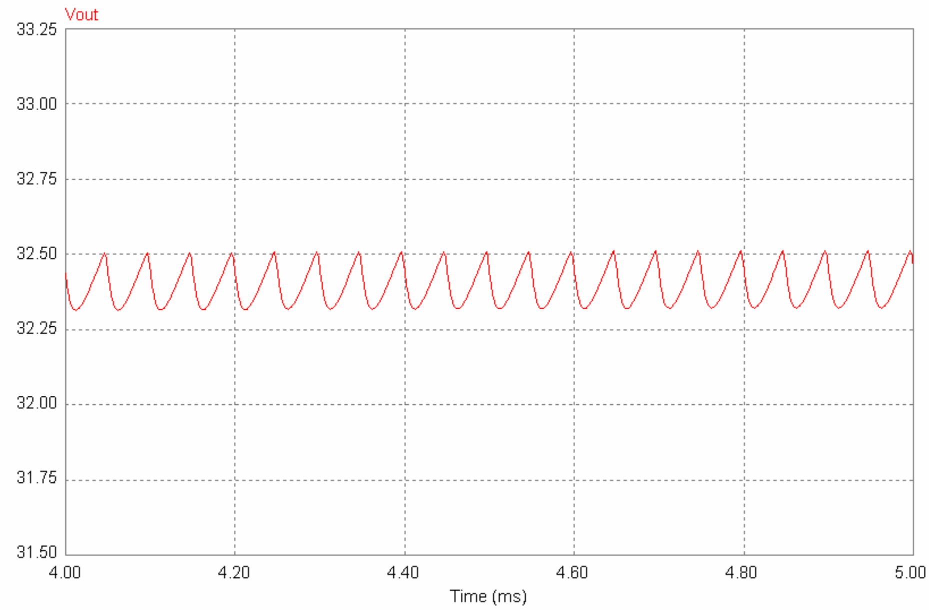

Fig.16 Ripple in the output voltage for 90% duty cycle of buck converter

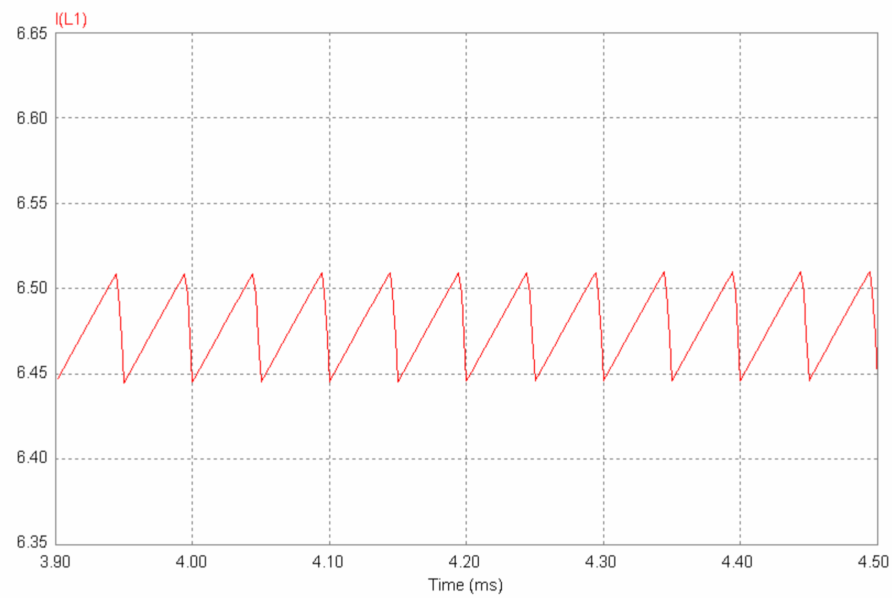

Fig.17 Inductor current for 90% duty cycle of buck converter

3.4.2. Simulation of buck converter for duty cycle of 50%

Voltage obtained in the output of the buck converter is 18.25 volt as shown in the waveform of the fig.18. Inductor current is continuous & varies from 3.5amp to 3.68 amp as per the design of the buck converter. Fig.19 shows the ripple obtained in the output voltage waveform. Value of the output voltage ripple is nearly 2.5%. This is almost equal to the Design calculation of the buck converter of 1%.

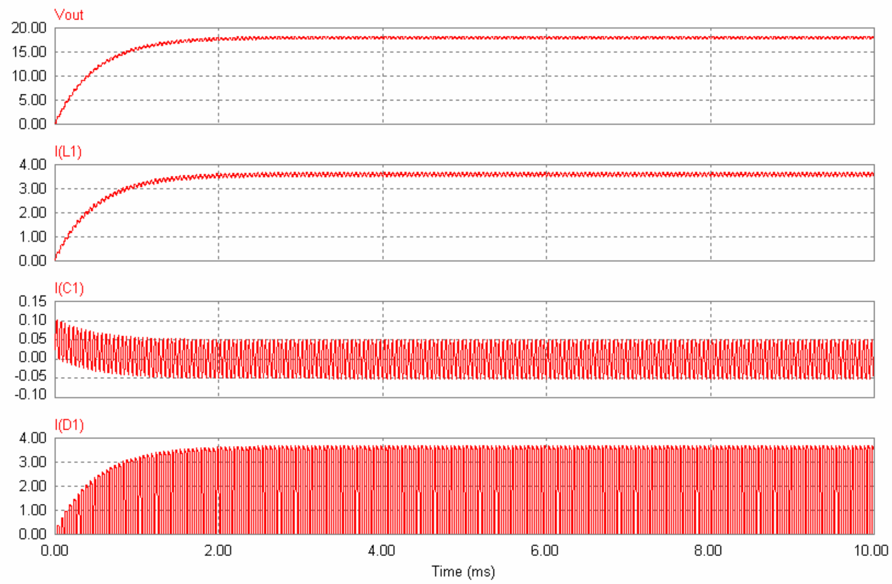

Fig. 18 Output voltage, inductor current, capacitor current, and diode current for 50% duty cycle of buck Converter

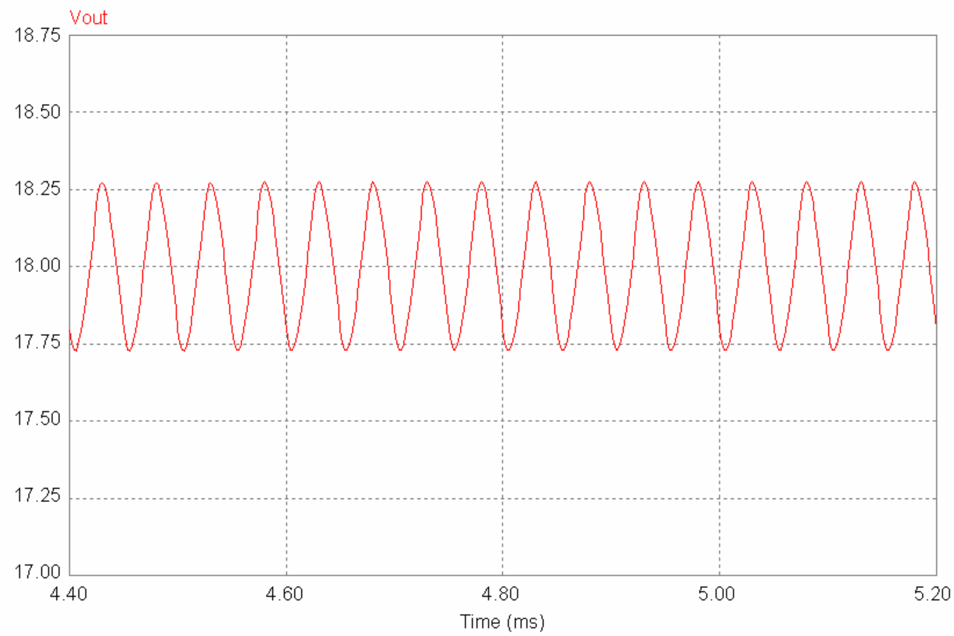

Fig.19 Ripple in output voltage for 50% duty cycle of buck converter

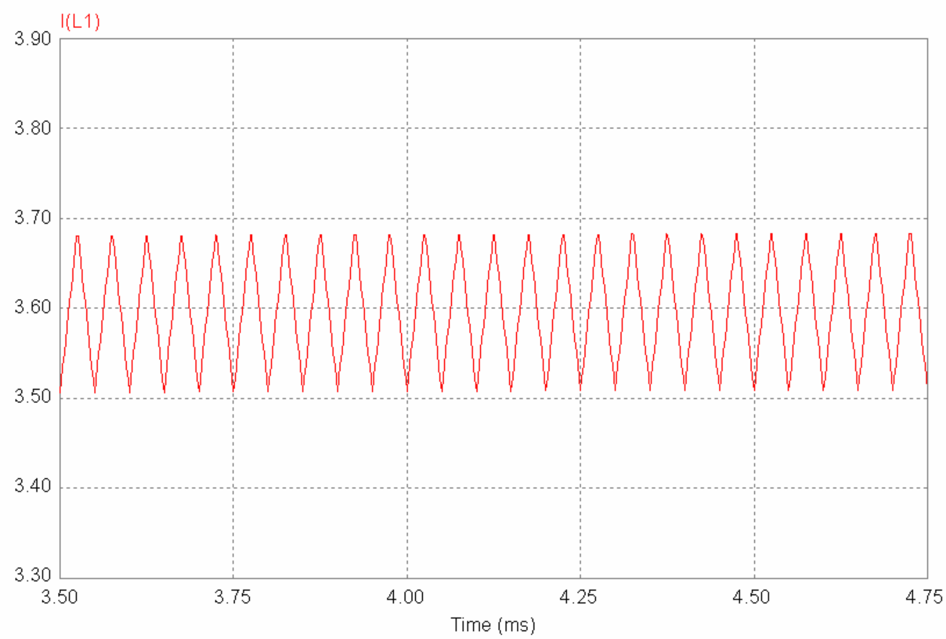

Fig.20 Inductor current for 50% duty cycle of buck converter

3.4.3. Simulation of buck converter for duty cycle of 20%

Voltage obtained in the output of the buck converter is 7.38 volt as shown in the waveform of the fig.21. Inductor current is continuous & varies from 1.38 amp to 1.50 amp as per the design of the buck converter. Fig.22 shows the ripple obtained in the output voltage waveform. Value of the output voltage ripple is nearly 4%. This is almost equal to the Design calculation of the buck converter of 1%.

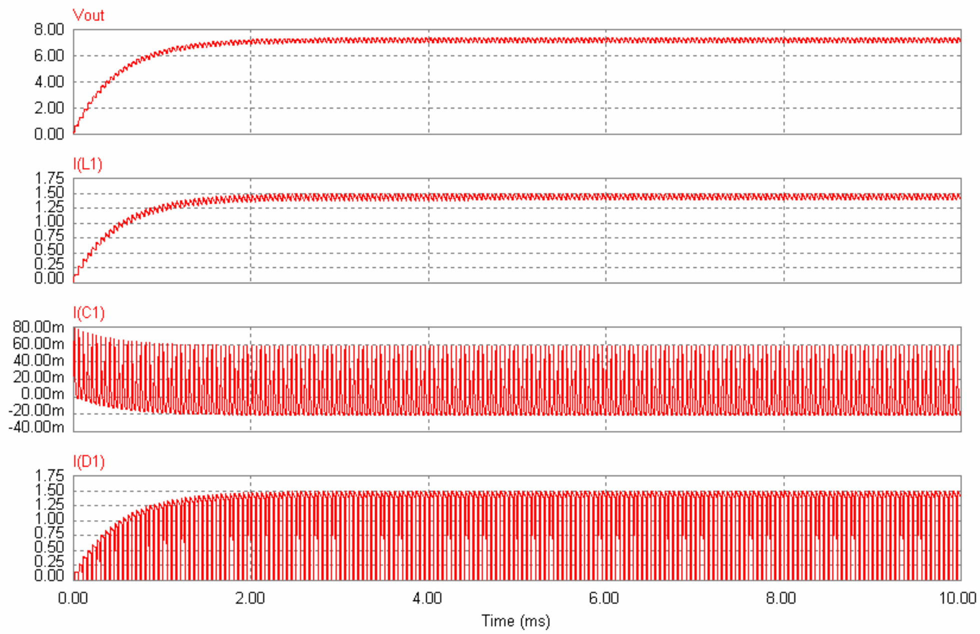

Fig.21 Output voltage, inductor current, capacitor current, and diode current for 50% duty cycle of buck Converter

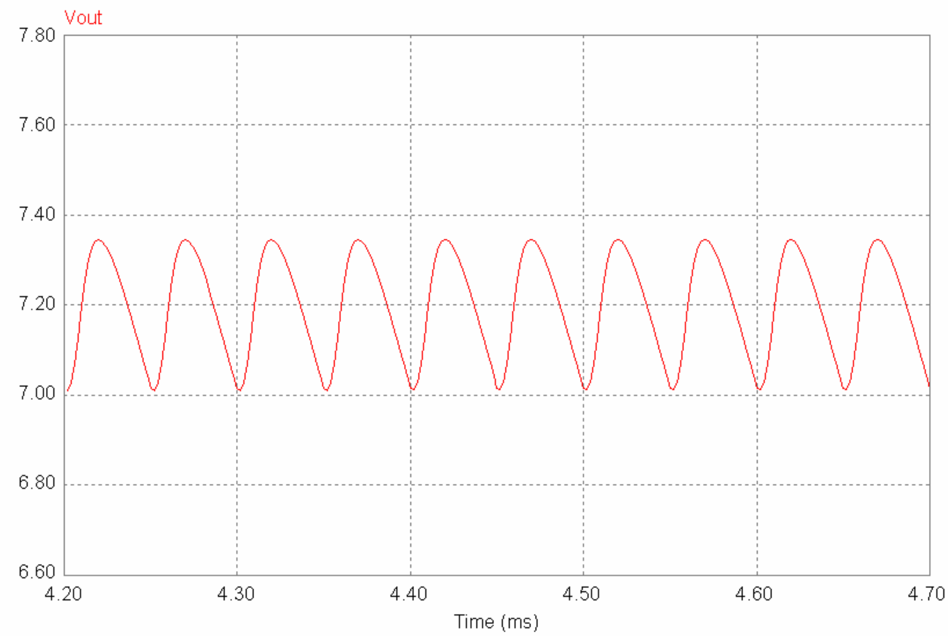

Fig.22 Ripple in output voltage for 20% duty cycle of buck converter

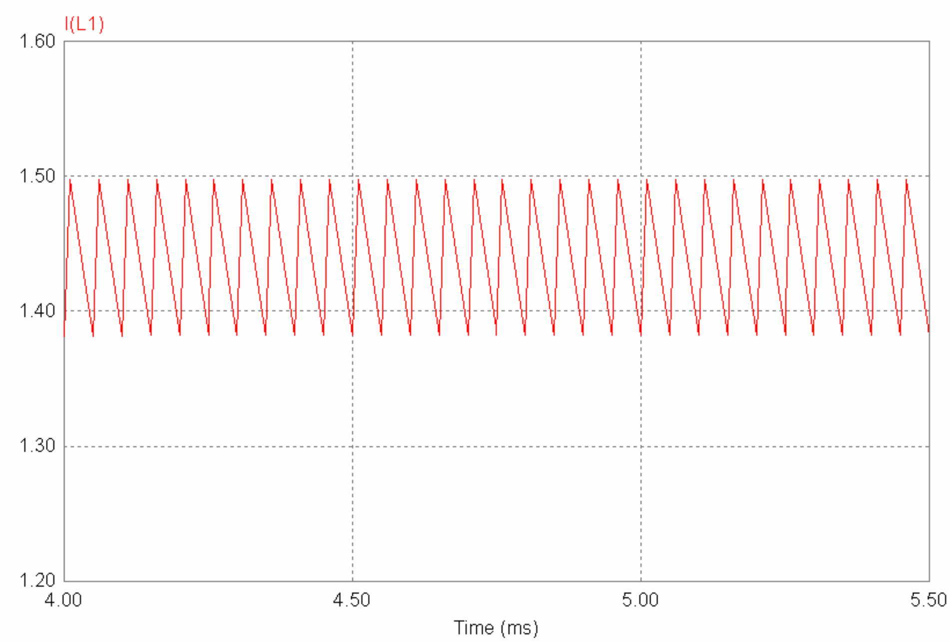

Fig.23 Inductor current for 20% duty cycle of buck converter

3.5. Conclusions

To obtain variable dc output voltage for inverter circuit, buck converter is better suited compare to linear regulated supply, because in the linear regulated supply, main output supply transistor operates in the linear region. Due to that there is a great deal of power loss associated with this arrangement, there by leading to a poor efficiency.

Selection of the inductor of value, 2.09 mH, satisfies the requirement of allowable current ripple of 1%. Selection of capacitor capacitor with the value of 1.5µH fulfills the purpose of allowable voltage ripple of 1%.

By varying the duty cycle from 0% to 90%, the output voltage can be varied from 0 to 32 volts. As the duty cycle decrease, output voltage decreases & ripple in the output voltage increases.

Chapter 4

THREE PHASE INVERTER FOR PM BLDC DRIVE

4.1. Introduction

A device that converts dc power into ac power at desired output voltage & frequency is called an inverter. Some industrial applications of the inverters are for adjustable speed ac drives, induction heating, stand by aircraft power supplies, UPS for computers, HVDC transmission lines etc.

For providing adjustable-frequency power to industrial applications, three phase inverters are more common than single-phase inverters. A basic three-phase inverter is a six-step bridge inverter. It uses minimum of six thyristors. In inverter terminology, a step is defined as a change in the firing from one thyristor to the next thyristor in proper sequence. For one cycle of 360°, each step would be of 60° interval for a six-step inverter. This means that thyristors would be gated at regular interval of 60° in proper sequence so that three phase ac voltage is synthesized at the output terminals of a six step inverter [10].

4.2. 180° control

Various control strategies are available to control the speed of the PM Brushless DC Motor. Strategies are 60° control & 120° control. In case of the 60° control, either the high side or low side switches are used for switching purpose to control the speed of the motor. The unused switches are normally shorted. The limitations of half control are the efficiency of the motor is very low. Each winding only conducts one direction current for two third of the time. Further more, the pulsation of torque is very high as the step size is reduced. In case of the 120° control, at any time two phases of the stator winding are energized. At any one instant, 2/3 of the phase is active. This means that copper utilization is around 67%. Each phase is turned on & off in an equal spacing of time. The switches are utilized at an even rate that yields equal losses.

In case of the180° control, anytime, all the three phase of the stator winding is energized. At any one instant, all the three phases are active, so there is 100% copper utilization.

Compare to above two strategies, lowest time the switches remains off so, pulsation in the torque is also lowest [13].

4.3. Simulation of buck converter fed PM Brushless DC Motor

Simulation is carried out in the PSIM Simulation tool. Simulation is carried out in both no-load & constant torque load. Speed of the motor is varied by varying the D.C. link voltage of the inverter with the help of the buck converter.

4.3.1 Simulation of buck converter fed PM Brushless DC Motor on No- load

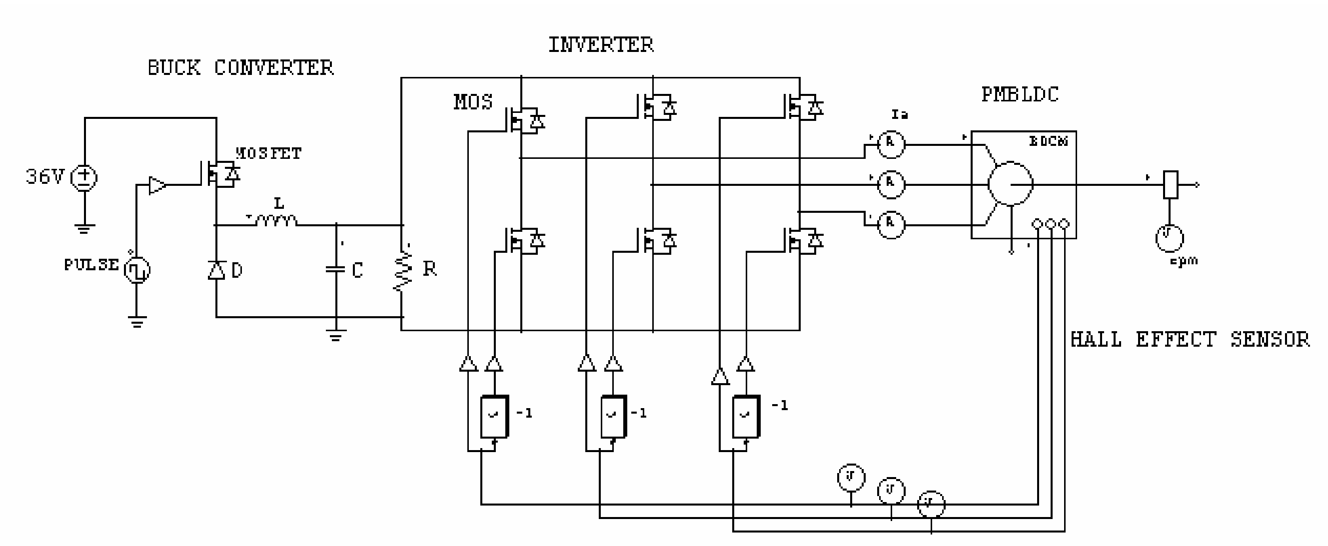

Fig.24 Buck converter fed PM BLDC drive on No-load

Simulation is carried out on no-load & by varying the duty cycle of the buck converter, speeds of the motor is controlled.

4.3.1.1. for 90% duty cycle of buck converter

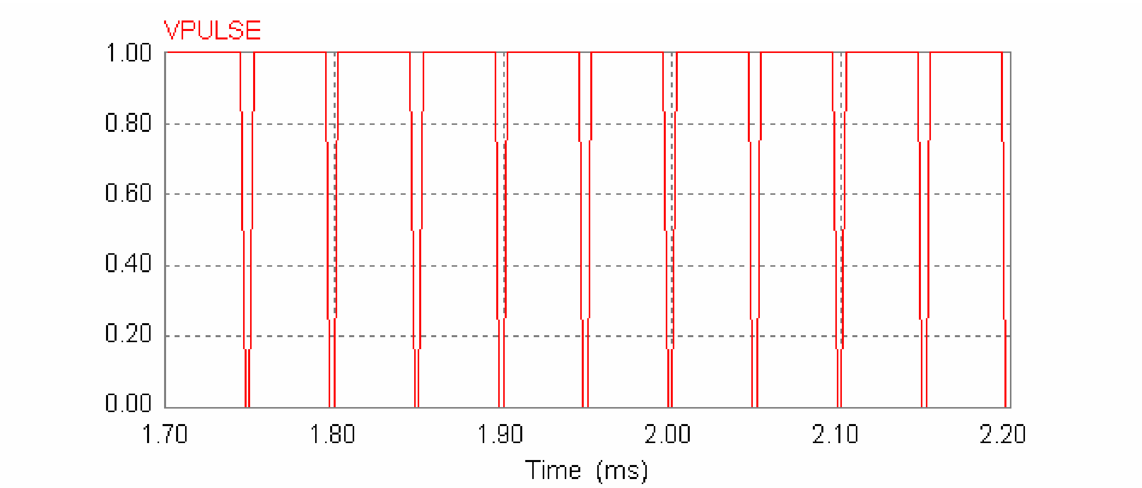

Fig.25 90% duty cycle of the buck converter

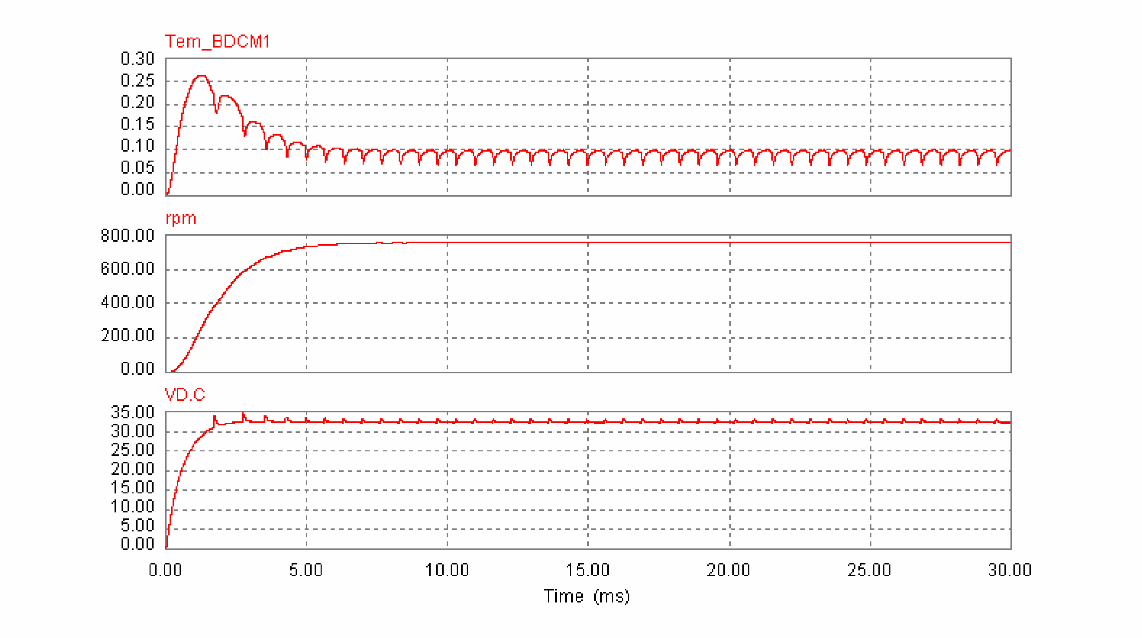

Fig.26 Torque, speed & D.C.link voltage for 90% duty cycle of buck converter for no Load

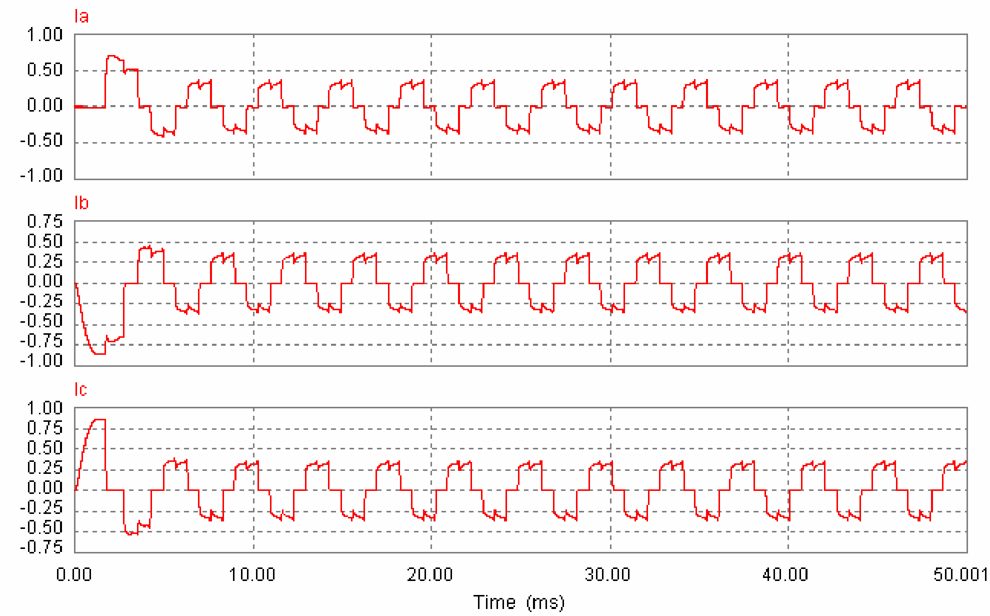

Fig.27 Inverter Phase currents for 90% duty cycle of buck converter

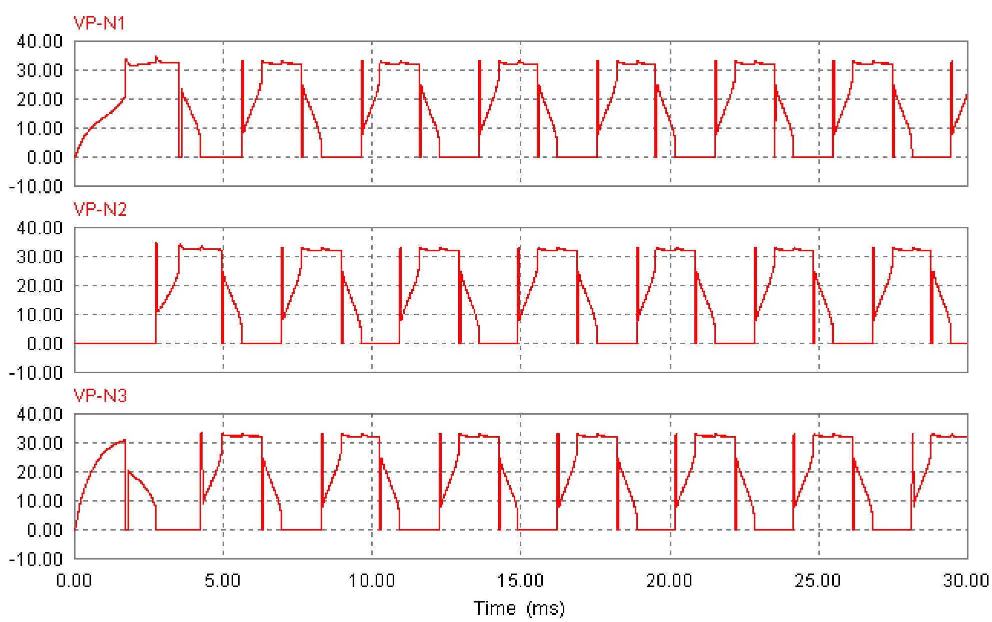

Fig.28 Inverter Phase to neutral voltages for 90% duty cycle of buck converter

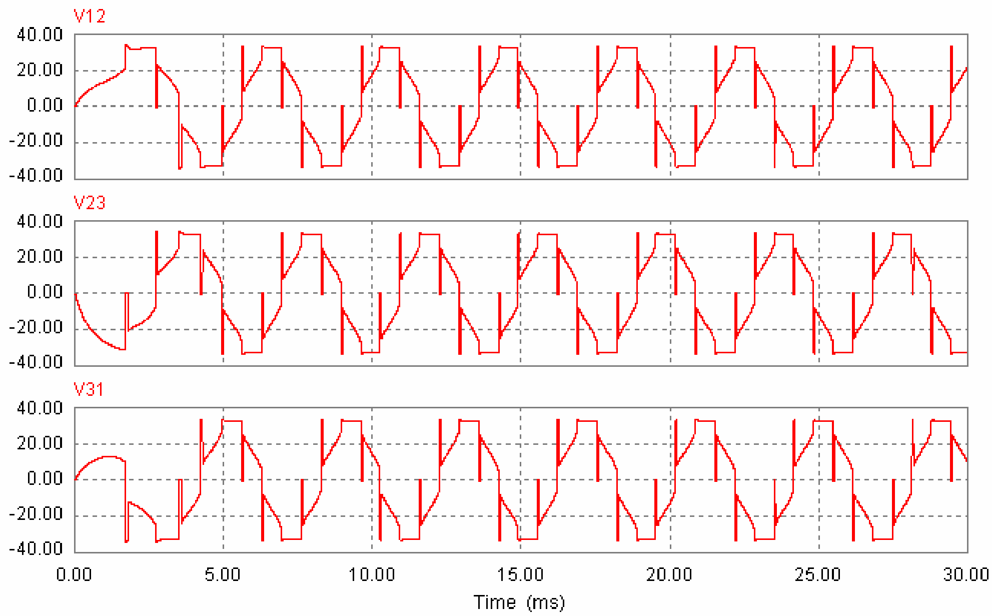

Fig.29 Inverter Phase to phase voltages for 90% duty cycle of buck converter

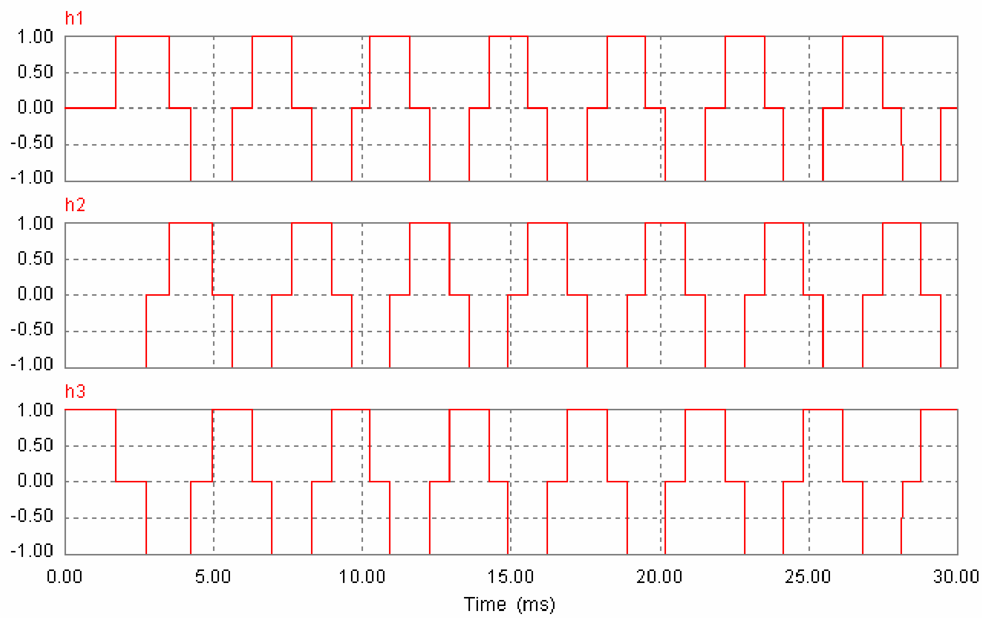

Fig.30 Obtained output from the hall-effect sensor

4.3.1.2. for 20% duty cycle of buck converter

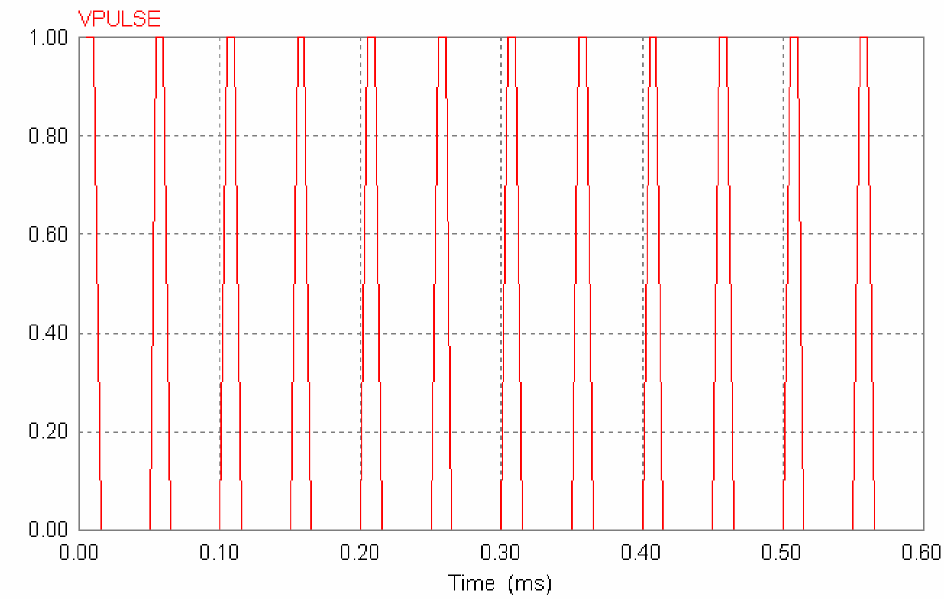

Fig.31 20% duty cycle of buck converter

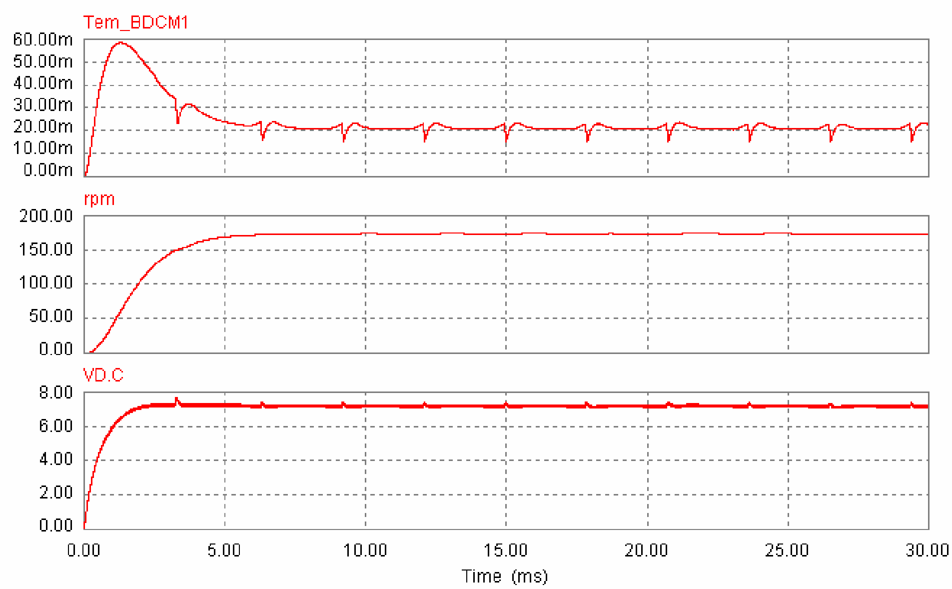

Fig.32 Torque, speed & d.c.link voltage for 20% duty cycle of buck converter

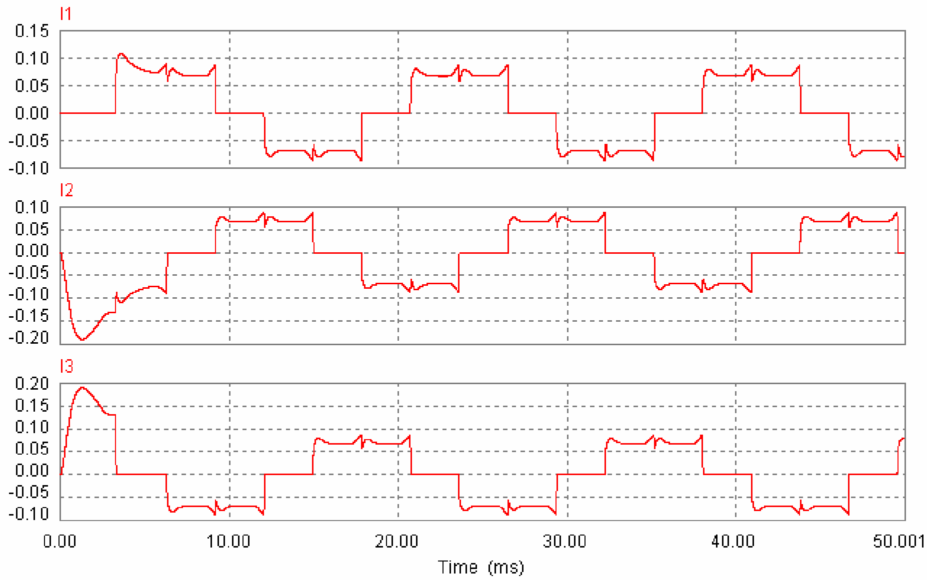

Fig.33 Phase currents for 20% duty cycle of buck converter

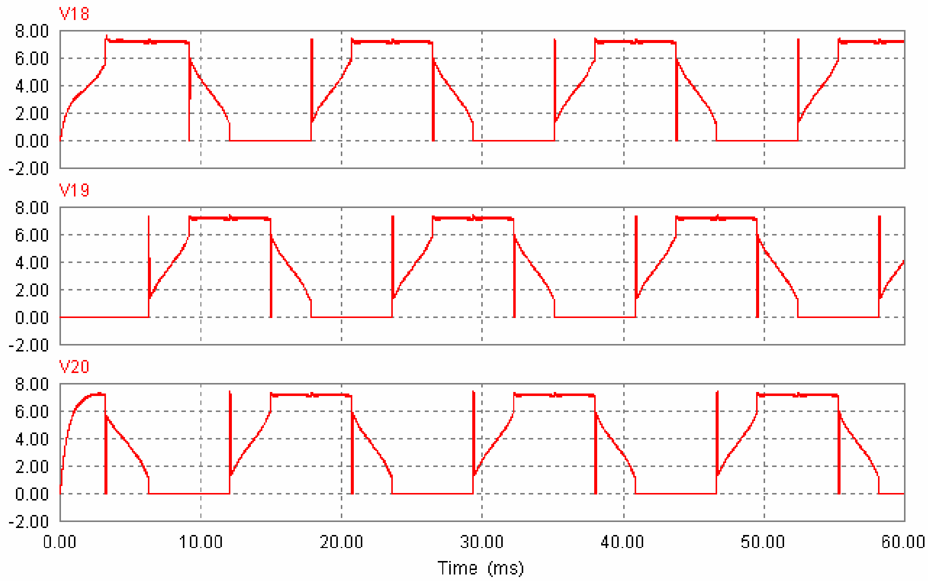

Fig.34 Phase to neutral voltages for 20% duty cycle of buck converter

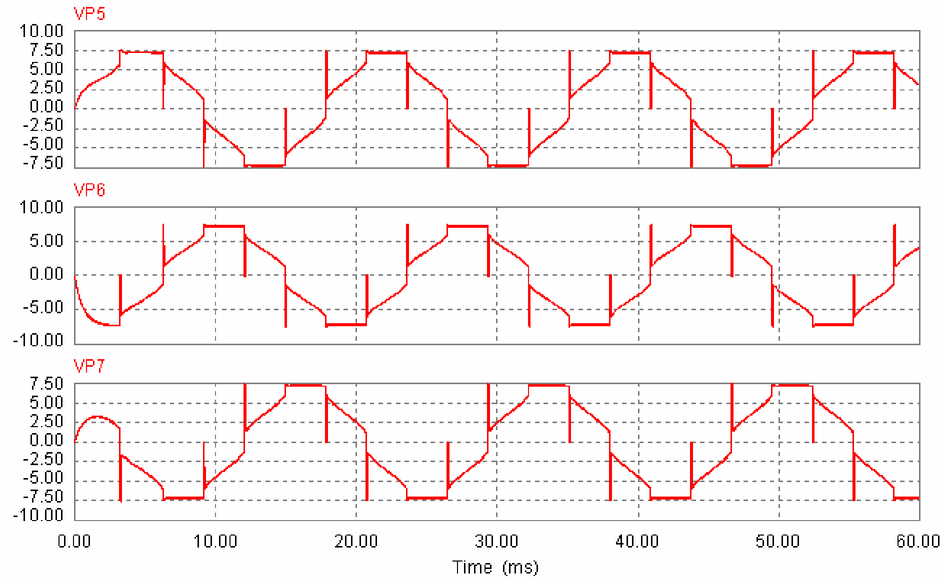

Fig.35 Phase to phase voltages for 20% duty cycle of buck converter

Table 4. Obtained speeds for various duty cycles of buck converter

Duty cycle	**Speed**
10%	85 rpm
20%	175 rpm
30%	265 rpm
50%	430 rpm
70%	600 rpm
80%	685 rpm
90%	760 rpm

4.3.2 Simulation of buck converter fed PM Brushless DC Motor on Constant torque Load

Simulation is carried out on constant torque load of 0.10-Nm & by varying the duty cycle of the buck converter, speeds of the motor is controlled.

4.3.2.1. for 90% duty cycle of buck converter

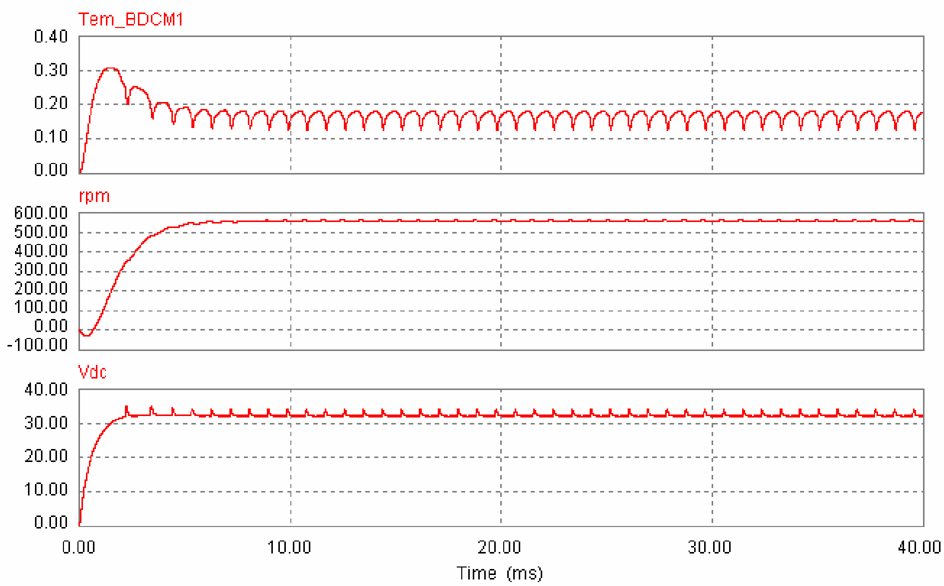

Fig.36 Torque, speed & D.C.link voltage for 90% duty cycle of buck converter for Constant torque load

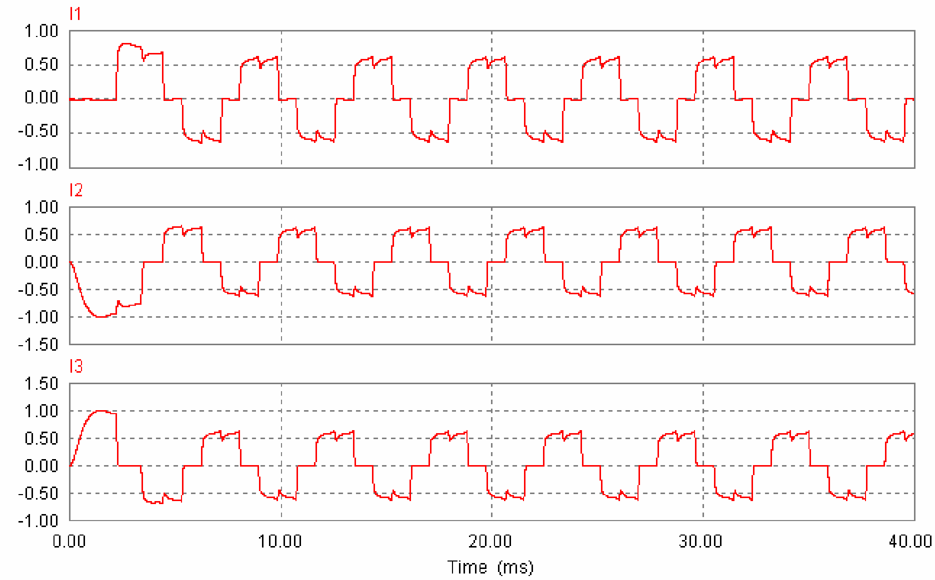

Fig.37 Phase currents for 90% duty cycle of buck converter

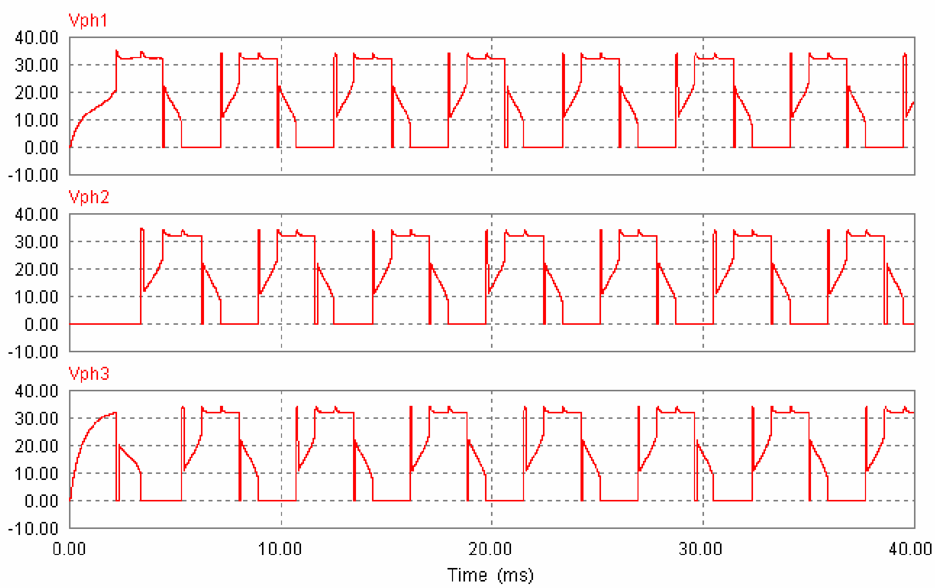

Fig.38 Phase to neutral voltage for 90% duty cycle of buck converter

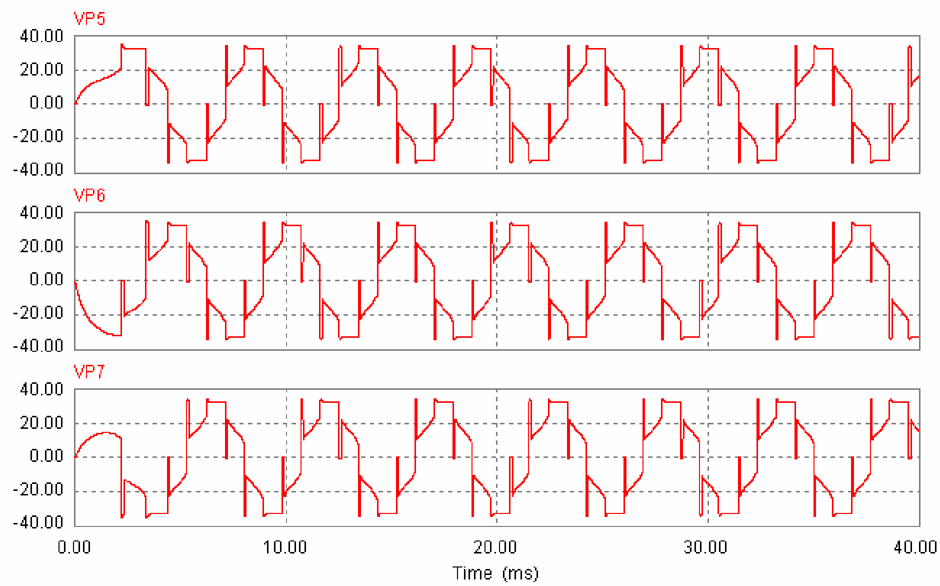

Fig.39 Phase to phase voltage for 90% duty cycle of buck converter

4.3.2.2. for 50% duty cycle of buck converter

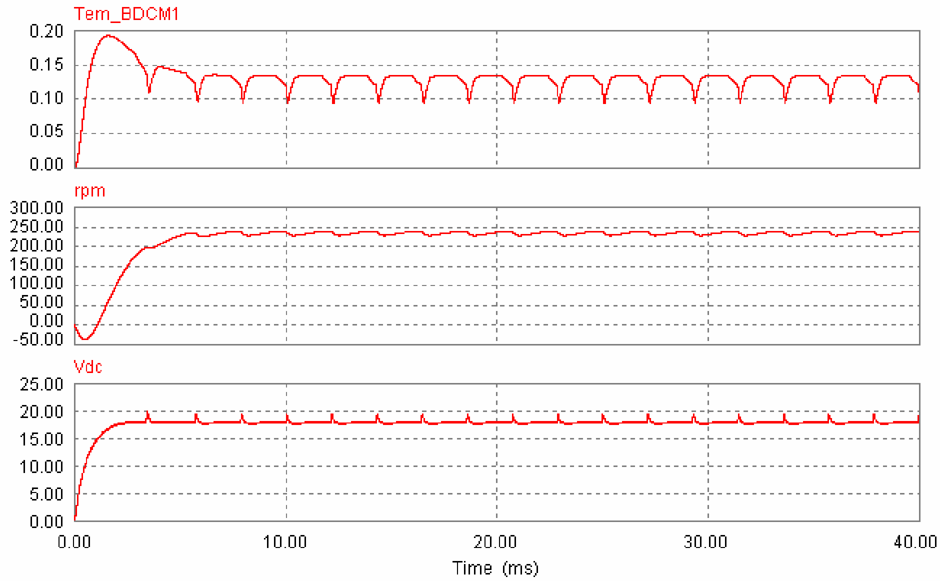

Fig.40 Torque, speed & D.C.link voltage for 50% duty cycle of buck converter

4.3.2.3. for duty cycle of 30%

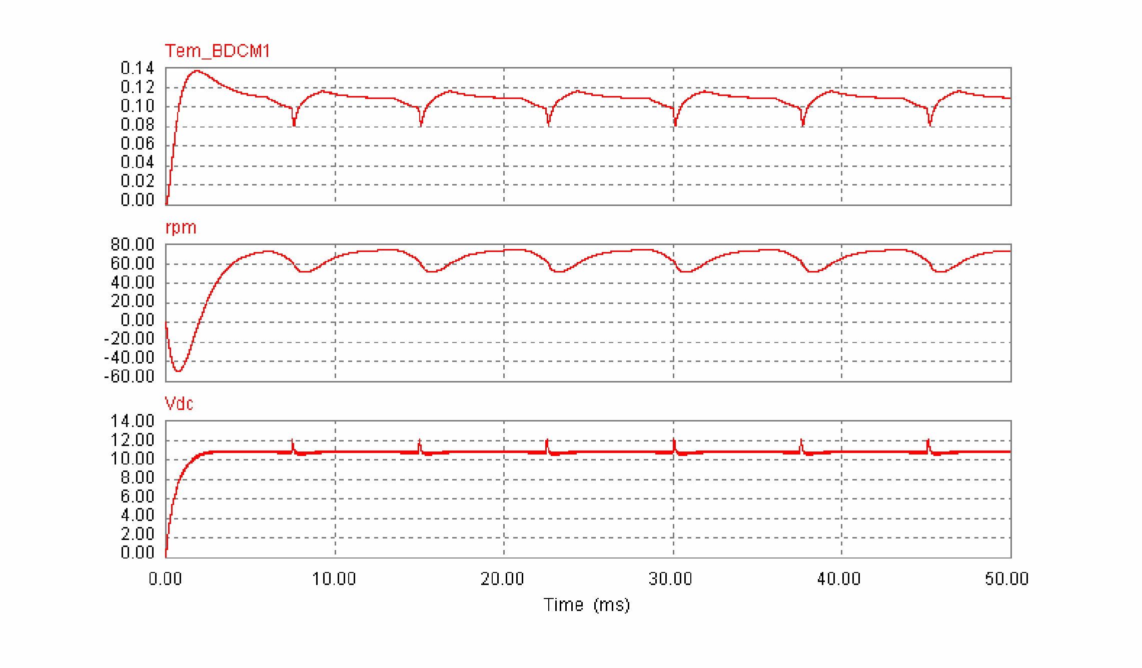

Fig.41 Torque, speed & D.C.link voltage for 30% duty cycle of buck converter

4.3.2.4. for duty cycle of 20%

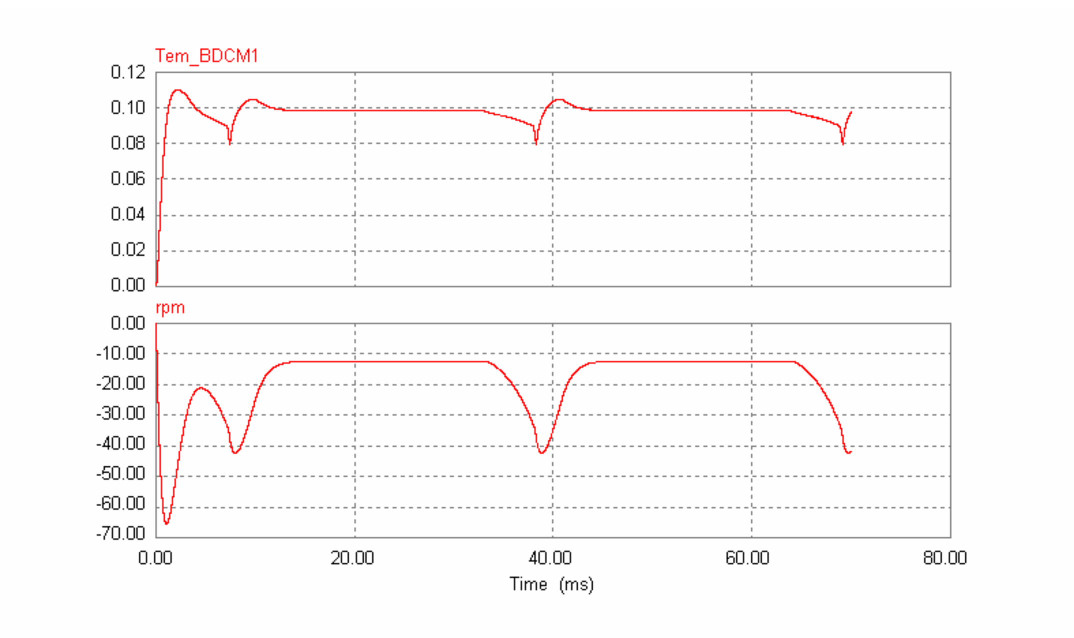

Fig.42 Torque & speed for 20% duty cycle of buck converter

4.4. Conclusions

(1) Among all the control strategies, 180° control strategy is the most preferable strategy to control the speed of PM Brushless DC Motor, because in this strategy, at any one instant all the three phases are active, so that there is 100% copper utilization. Due to the lowest time the switches remain off, pulsation in the torque is lowest compare to 60° control & 120° control

(2) Firstly the motor is driven on no load & by changing the duty cycle of the buck converter from 10% to 90%, variation in the speed is obtained from 85 rpm to 760 rpm.

(3) Motor is driven on the constant torque load of 0.1 N-m. For the 90% duty cycle of buck converter, achieved speed is 660 rpm. For the duty cycle of buck converter below 40%, speed of the motor remains zero or motor start to rotate in the reverse direction during the starting. So, to control the speed of motor properly, duty cycle of buck converter should be varied between 40% to 90%.

Chapter 5

DEVELOPMENT OF THE BUCK CONVERTER FED PM BLDC DRIVE

5.1. Overview of implementation

Since the simulation results were promising, buck converter fed VSI fed BLDC Drive has been implemented. Each block of the implementation is described & relevant experiment results are presented. The hardware blocks that have been described are pulse generator for buck converter, buck converter, control & driver circuit of the three phase inverter, and hall sensor.

5.2. Buck converter

5.2.1 Pulse generator for MOSFET

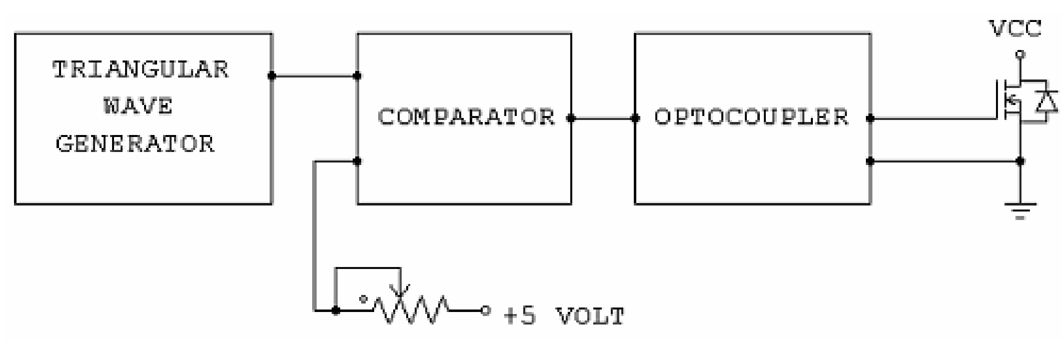

Fig.43 Scheme for the generation of pulse for buck converter

Pulses for the buck converter are generated by comparing triangular wave with the variable d.c.voltage. So, by varying the duty cycle of the MOSFET, variable d.c.voltage is obtained at the output. Triangular wave is generated by using the op-amp & the frequency of the triangular wave is 20KHZ. Amplitude of triangular wave is 7 volt. As shown in fig.44.Due to higher switching frequency, opamp used as a comparator is of high slew rate of 13v/µs.

Optocoupler I.C. 6N 135 is used as a driver for the MOSFET as shown in fig.49 Propagation delay of this optocoupler is 0.8µs. & Superior CMR of 10kv/µs, as well as high speed of 1MBit/s.

5.2.2. Triangular wave generator

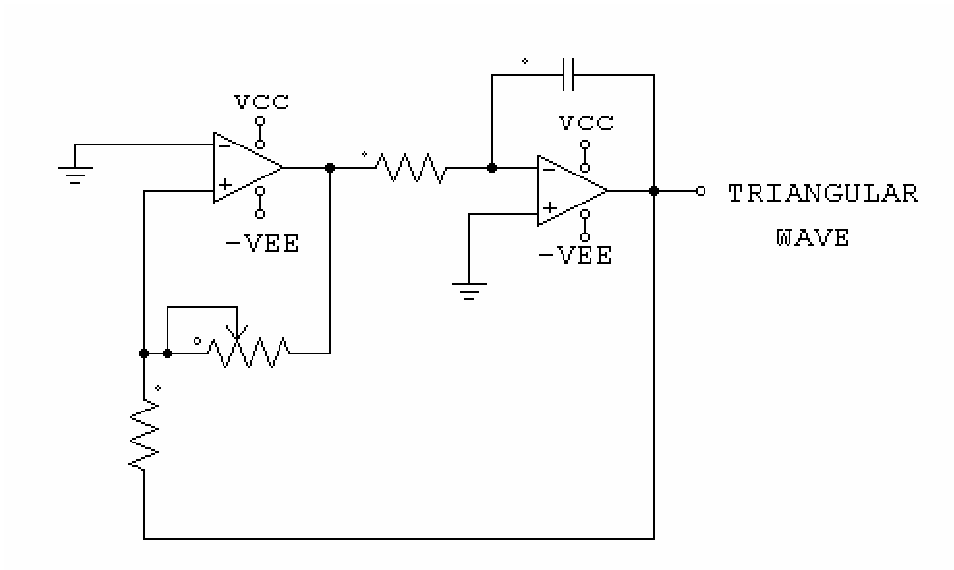

Fig.44 Triangular wave generator.

Fig.45 shows the obtained triangular wave having frequency of 20 kHz. by comparing this triangular wave with variable d.c. voltage, pulses obtained at the output of the comparator. By varying the D.C. voltage, various duty cycles are obtained.

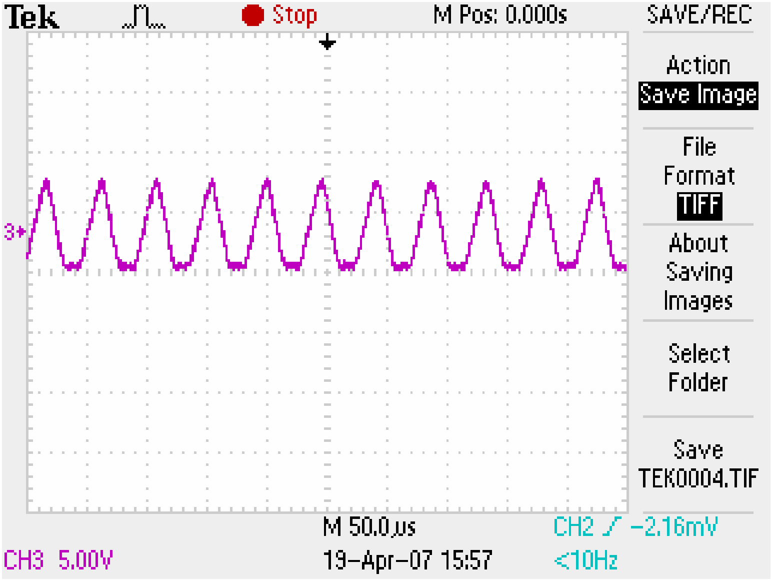

Fig.45 Obtained Triangular wave

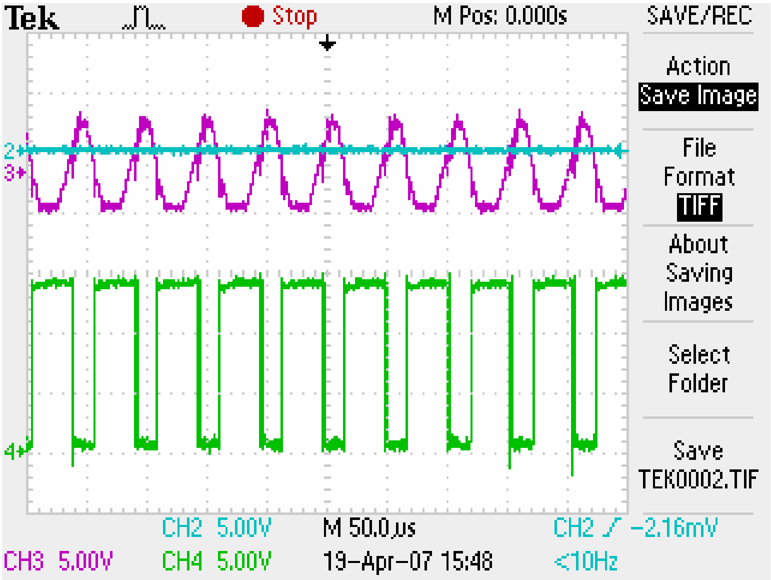

Fig.46 Obtained pulse for MOSFET for duty cycle of 70%

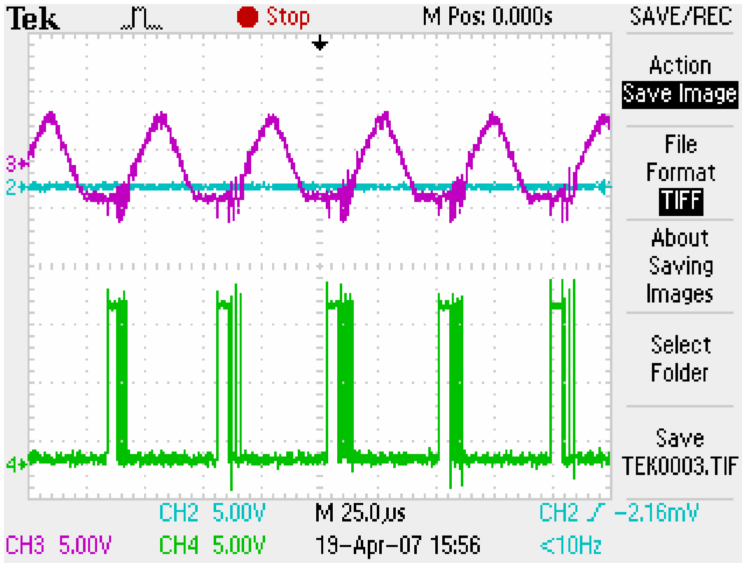

Fig.47 Obtained pulse for MOSFET for duty cycle of 20%

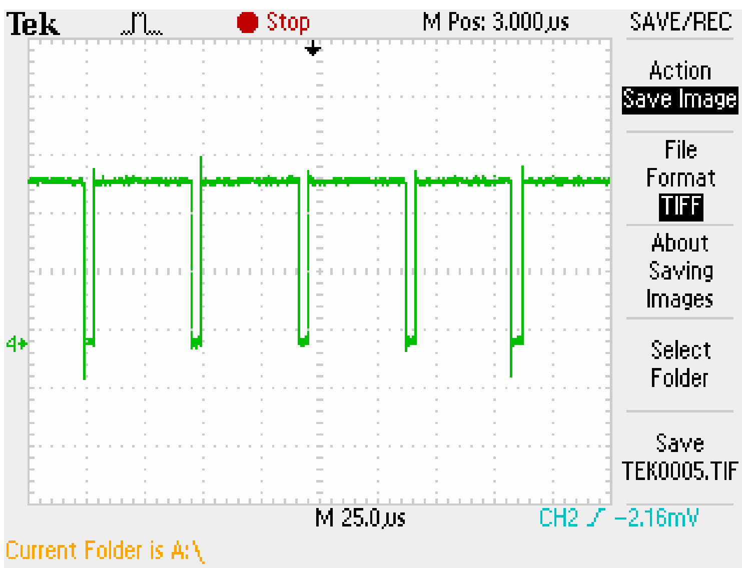

Fig.48 Pulse obtained for duty cycle of 90%

5.2.3. Opto coupler as Driver

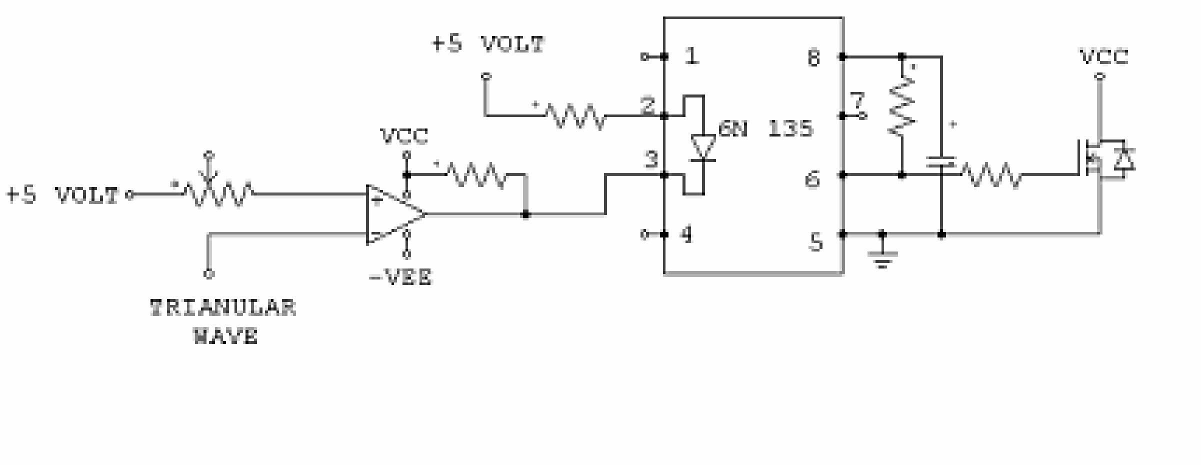

Fig.49 Opto coupler as a MOSFET driver

Optocoupler I.C. 6N 135 is used as a driver for the MOSFET as shown in fig.49 Propagation delay of this optocoupler is 0.8µs. & Superior CMR of 10kv/µs, as well as high speed of 1MBit/s. MOSFET being used for switching purpose is IRF 530 with the voltage rating of 110V & current rating of 14 amp.

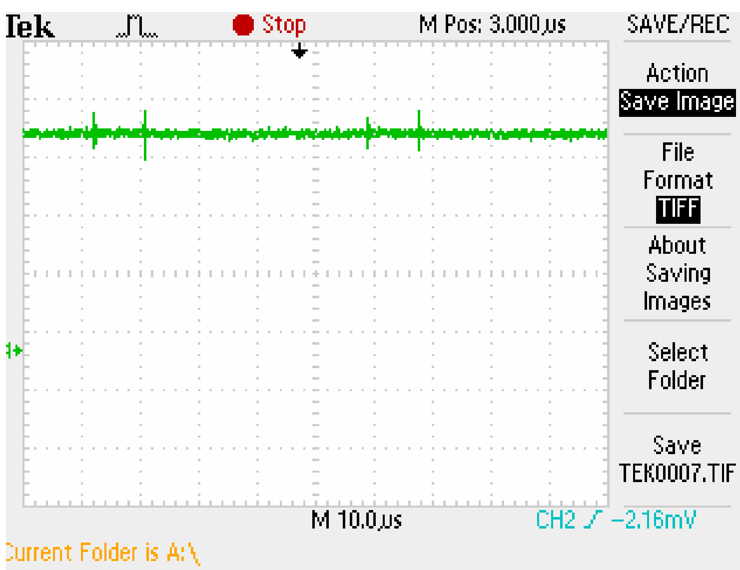

Fig.50 Obtained output of Buck converter output for duty cycle of 80%

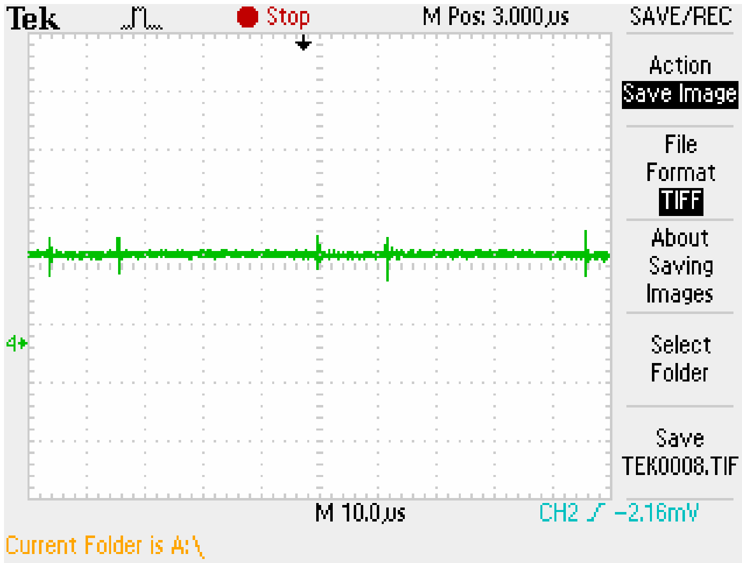

Fig.51 Obtained output of Buck converter output for duty cycle of 25%

Figure 50. Shows the output of the buck converter for duty cycle of 80%. Obtained output is of 28 volt. Fig.51 shows the output of the buck converter for duty cycle of 25%. Obtained output is of 9volt.

5.3. Three phase inverter

5.3.1. Block diagram of Control circuit of the Inverter

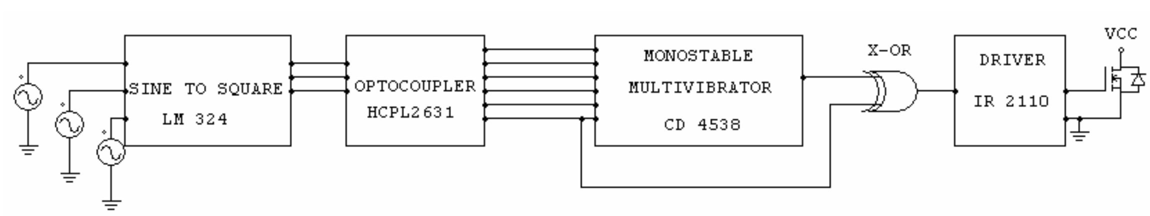

Fig.52 Block diagram of control circuit of 3-phase inverter

Figure.52 shows the scheme for the generation of the pulses for the 3-phase inverter. 3-phase inverter is designed for the 180° conduction mode. In this scheme, each switch conducts for 180°. Dead time added between the two same phase pulses is 10μs.

Three sine waves taken from the 3-phase transformer are converted into the square wave by using the opamp. LM 324, as shown in fig.53. Then by using the optocoupler HCPL 2631, square wave is inverted & finally 6-pulses are obtained. The next job is to provide dead time between the two same phase pulses. Dead time is provided by using the Monostable Multivibrator & EX-OR I.C. Monostable Multivibrator is triggered on the positive edge of the input pulses as shown in fig. & then after by EX-ORING these two pulses, dead time between two pulses is obtained.

5.3.2. Sine wave to square wave generator

Using I.C.-LM 324 i.e. Low power quad operational amplifier, square wave is obtained from the sine wave as shown in fig.54. The three square wave is obtained of +5v amplitude as shown in fig.54. This three 120° phase shifted square wave is given to the optocoupler I.C. named HCPL 2631 in which there are two optocoupler to invert the pulse. Finally 6-pulses are obtained at the output of the optocouplers.

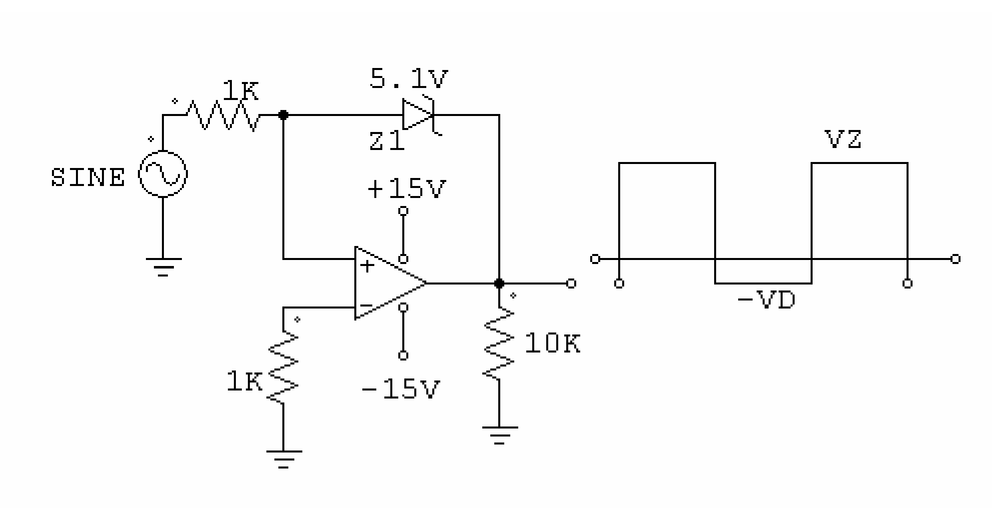

Fig.53 Sine wave to square wave generator

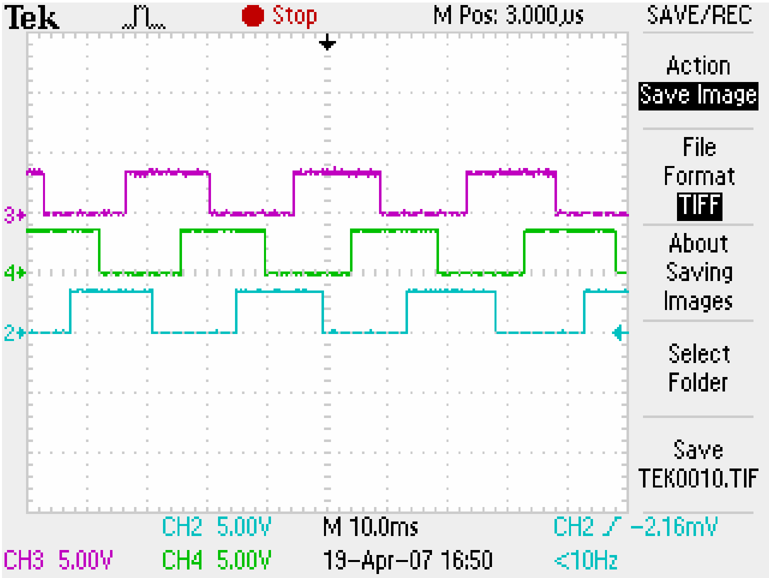

Fig.54 Obtained square waves from sine waves

5.3.3. Opto coupler as an Inverter

This three 120° phase shifted square wave is given to the optocoupler I.C. named HCPL 2631 in which there are two optocoupler is there to invert the pulse. Finally output of this optocoupler is 6-output pulses.

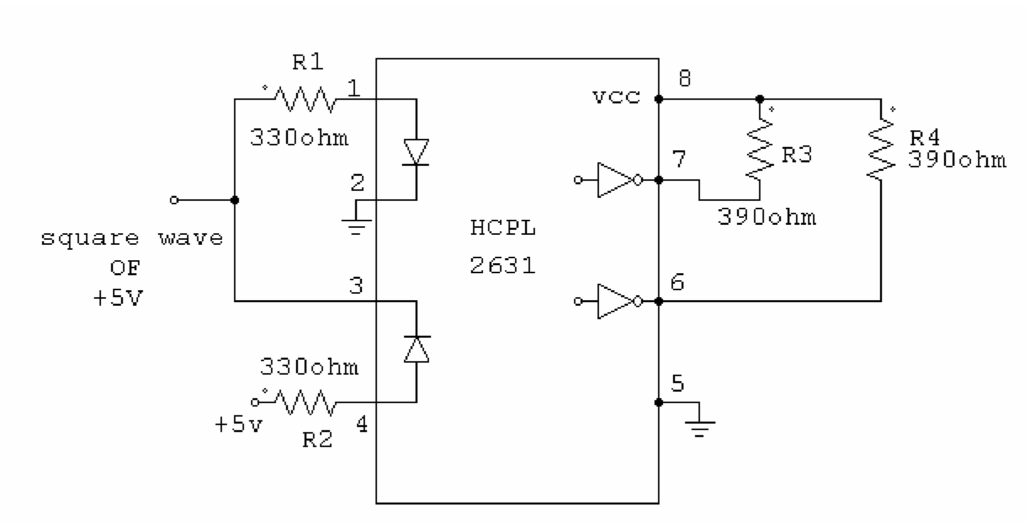

Fig.55 Opto coupler as an Inverter

Two inverted pulses are obtained at output of the optocoupler. Pin 6 & 7.

Selection of the R1 & R2:-

R1, R2= $\frac{5-1.5}{10mA} = 330\Omega$

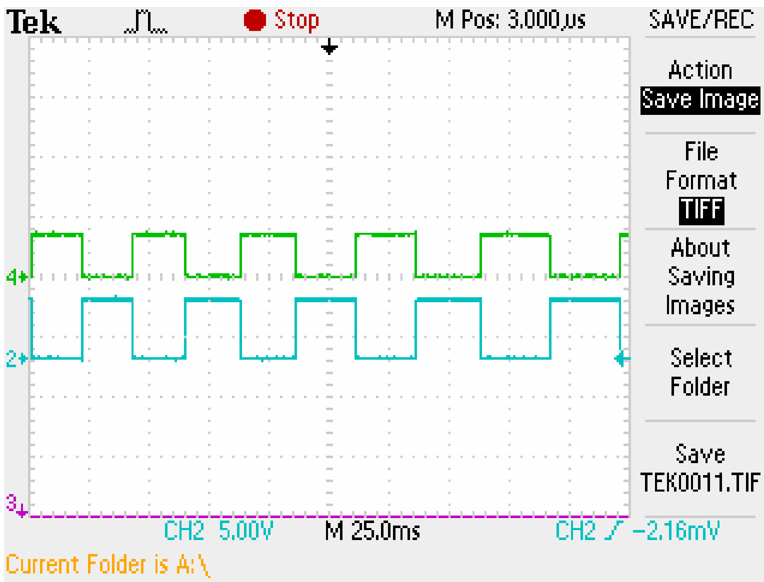

Fig.56 Obtained Output from the optocoupler

5.3.4. Generation of Dead time

Fig. 57 shows the circuit diagram for generation of the dead time between two same phase MOSFET pulses. Obtained dead time is of the 10µS as shown in fig. 59.

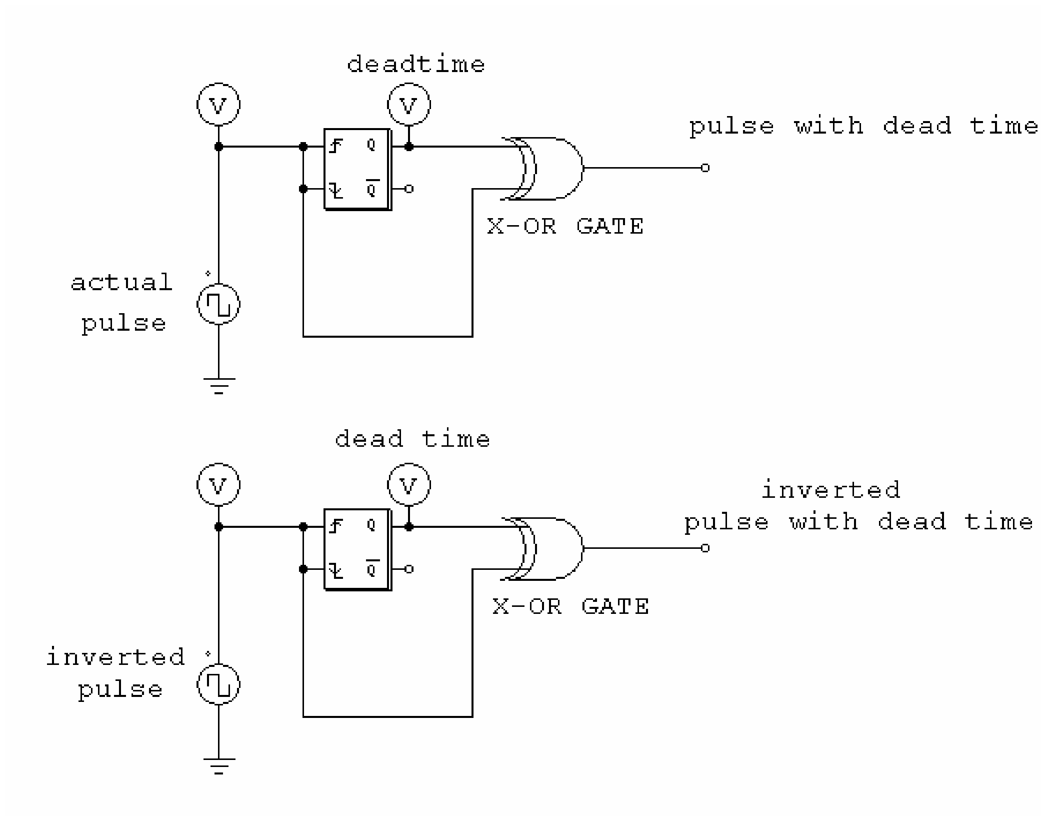

Fig.57 Dead time generator for MOSFET of the Inverter

Dead time is generated by using the Monostable Multivibrator & EX-OR I.C. Monostable Multivibrator is triggered on the positive edge of the input pulses as shown in fig.58 & then after by EX-ORING these two pulses, dead time between two pulses is obtained, as shown in fig.59

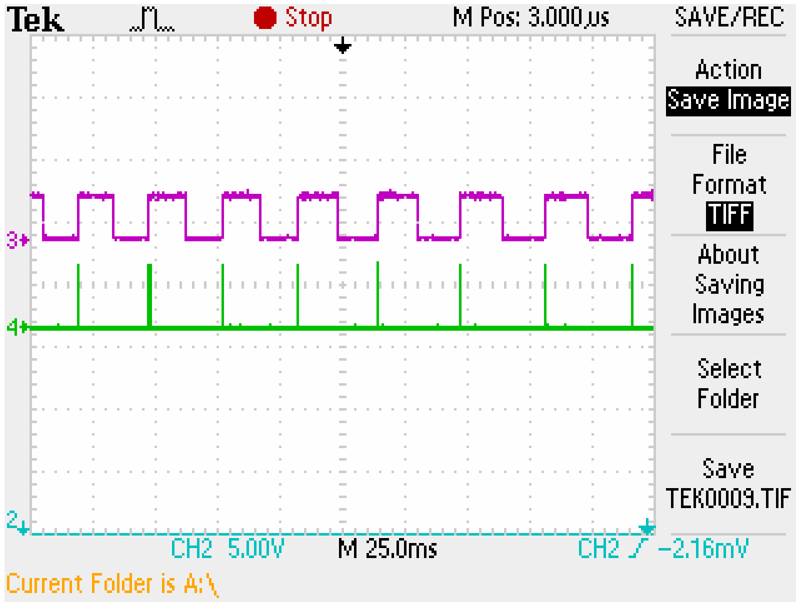

Fig.58 Obtained Positive edge triggering of the input pulse

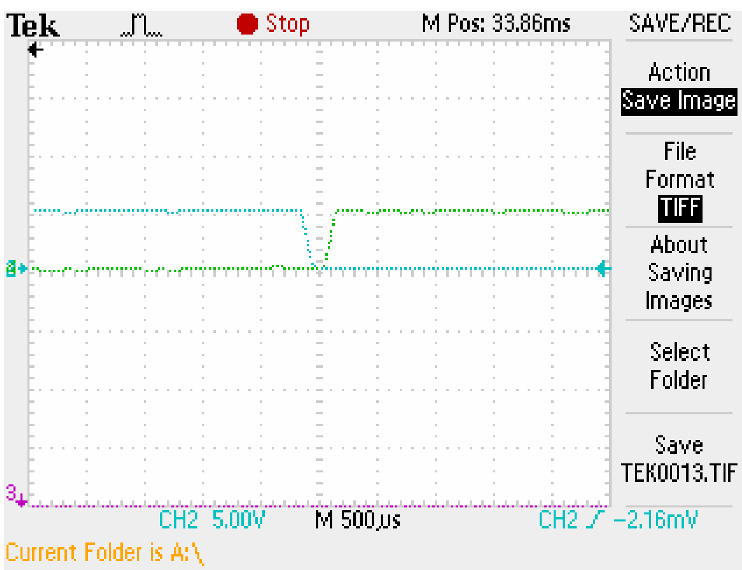

Fig.59 Obtained dead time between the pulse of the same phase MOSFETs

5.3.5. MOSFET Driver IR 2110

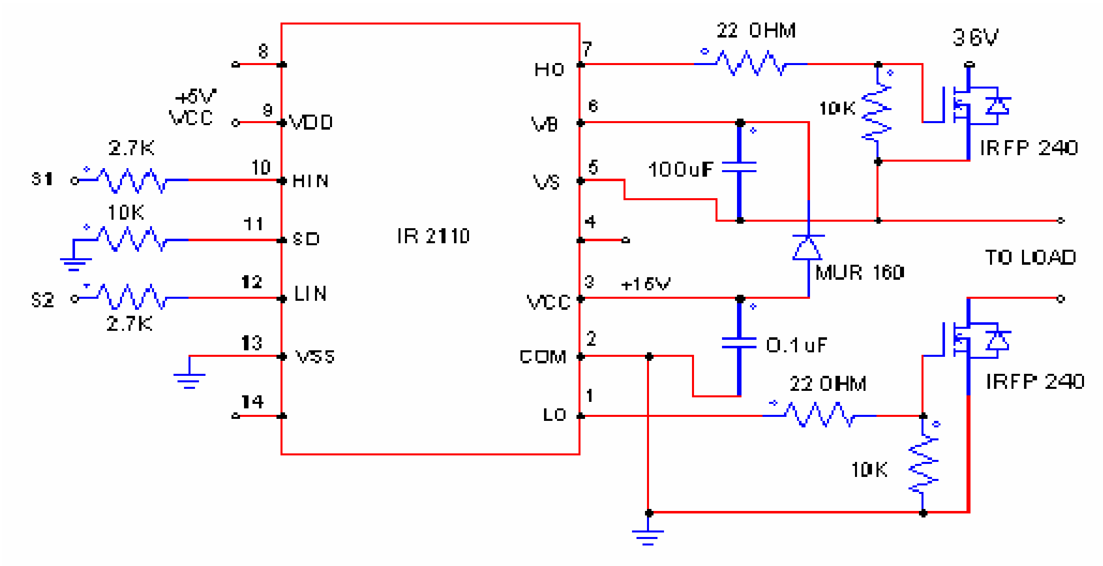

Fig.60 Connection diagram of driver I.C. IR 2110

5.3.5.1. Features of Driver

- Floating channel designed for bootstrap operation.
- Gate drive supply range from 10v to 20v.
- Under voltage lockout for both channel
- Cycle by cycle edge triggered shutdown logic.
- CMOS Schmitt triggered inputs with pull-down.
- Matched Propagation delay for both channels.
- Output in phase with inputs.
- 3.3volt logic compatible.

5.3.5.2. Selection of Bootstrap capacitor for Driver

As shown in Figure 60, the bootstrap diode and capacitor are the only external components strictly required for operation in a standard PWM application. Local decoupling capacitors on the VCC (and digital) supply are useful in practice to compensate for the inductance of the supply lines. The voltage seen by the bootstrap capacitor is the VCC supply only. Its capacitance is determined by the following constraints:

1. Gate voltage required to enhance MGT
2. I_{QBS} - quiescent current for the high-side driver circuitry
3. Currents within the level shifter of the control IC
4. MGT gate-source forward leakage current
5. Bootstrap capacitor leakage current

Factor is only relevant if the bootstrap capacitor is an electrolytic capacitor, and can be ignored if other types of capacitor are used. Therefore it is always better to use a non-electrolytic capacitor if possible. The minimum bootstrap capacitor value can be calculated from the following equation

$$C \geq \frac{15 \times 2\left[2Qg + \frac{I_{qbs(\max)}}{f} + Q_{ls} + \frac{I_{cbs(leak)}}{f}\right]}{V_{CC} - V_f - V_{LS} - V_{\min}}$$

The bootstrap diode must be able to block the full voltage seen in the specific circuit, when the top device is on and is about equal to the voltage across the power rail. The current rating of the diode is the product of gate charge times switching frequency. The high temperature reverse leakage characteristic of this diode can be an important parameter in those applications where the capacitor has to hold the charge for a prolonged period of time. For the same reason it is important that this diode have an ultra-fast recovery to reduce the amount of charge that is fed back from the bootstrap capacitor into the supply.

According to equation,

$$C \geq \frac{15\times 2\left[2Qg+\frac{I_{qbs(\max)})}{f}+Q_{ls}+\frac{I_{cbs(leak)}}{f}\right]}{V_{CC}-V_{f}-V_{LS}-V_{\min}}$$

$$C \geq \frac{15\times 2\left[(2\times 60nC)+\frac{230\times 10^{-6}}{50}+(5\times 10^{-9})+\frac{16\times 10^{-6}}{50}\right]}{15-1-10-2.5}$$

$$C=\frac{141.76}{1.5}$$

C=94.5μF

C=100μF

Thus minimum value of the capacitor should be 94μF.

5.3.5.3. Selection Gate resistance for MOSFET

$$R_{GATE}=\frac{V_{CC}-V_{EE}-V_{OL}}{I_{OL}}=\frac{48-0-0.1}{2.5}=22\Omega$$

Thus, from the above equation, required gate resistance can be found from the above equation. The value of gate resistance is 22Ω.

5.3.6. Power Circuit

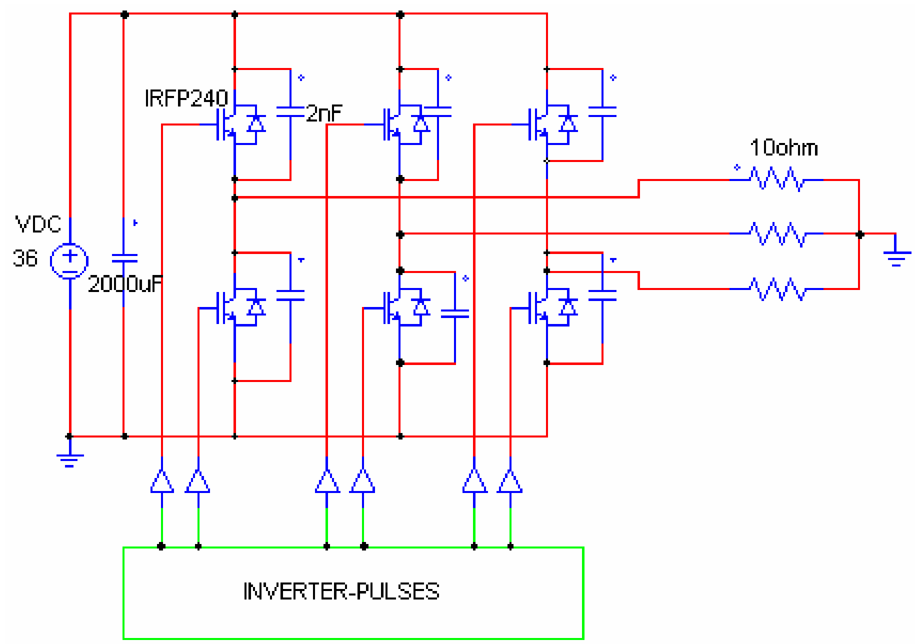

Fig.61 Power circuit of three phase inverter

5.4. Testing of inverter on resistive load

Inverter is first, tested on resistive load. Value of the resistor used as load is 10Ω. As shown in fig.62, phase to phase voltages obtained are +Vdc to –Vdc peak to peak value. And phase to neutral is 2vs/3 i.e.24 volt. R.M.S. Value obtained is 24 volt.

There are some spikes obtained in the inverter output voltage waveform, which are due to the switching actions of the MOSFETs as well as the parasitic inductance of the wires of the phase of the inverter. Spikes are filtered by putting one d.c.link capacitor of 2000µF as well as connecting capacitors of 2nF between the drain & source of the MOSFETs.

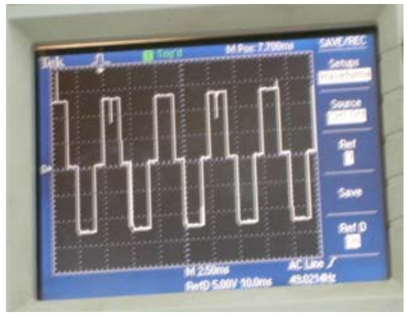

Fig.62 Obtained Phase to phase voltage of the inverter

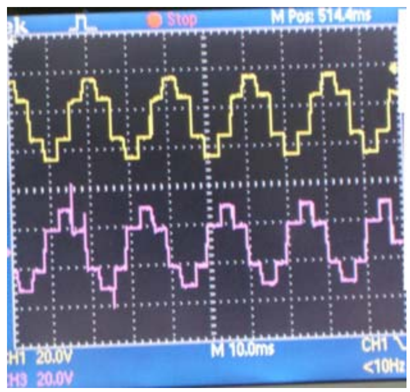

Fig.63 Obtained Phase to neutral voltage of the inverter

Figure 62 & fig.63 shows the phase to phase voltage as well as the phase to neutral voltage of the inverter output voltage. Inverter output voltages are obtained for different d.c.link voltages. Below a table 5 is given, which shows the output waveform values for various d.c.link voltages.

Table 5. Inverter output voltages

$V_{.D.C.}$	$V_{P\text{-}P}$	$V_{P\text{-}N}$	$V_{RMS(P\text{-}P)}$
12v	$-V_{D.C.}$ to $+V_{D.C.}$	7.5v	8v
24v	$-V_{D.C.}$ to $+V_{D.C.}$	15v	16.2v
36v	$-V_{D.C.}$ to $+V_{D.C.}$	22.5v	24v

5.5. Hall effect sensor

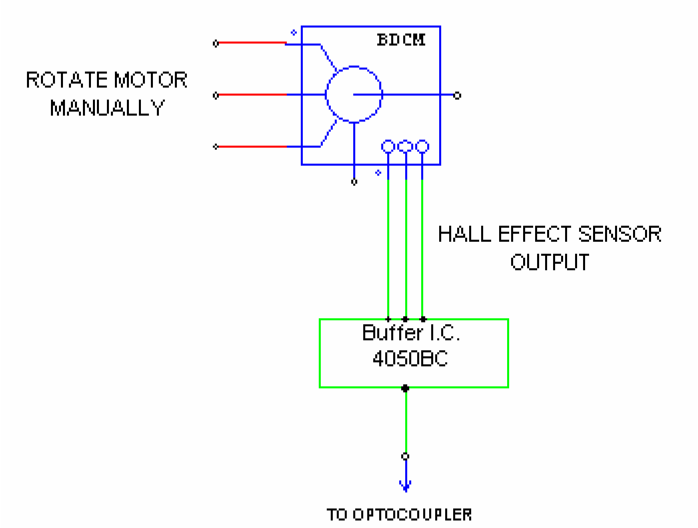

Fig.64 Used buffer I.C. for Hall Effect sensor

Motor is driven first, manually & observed the signals obtained at the output of the Hall Effect sensor. Signals obtained are 120' phase shifted to each other as shown in fig.65. Again due to the high impedance of the Hall Effect sensor, loading effect of the opto coupler I.C. used as inverter is obtained. This problem of the loading is solved by connecting one buffer I.C.-4050BC between the hall-effect sensor & optocoupler I.C.

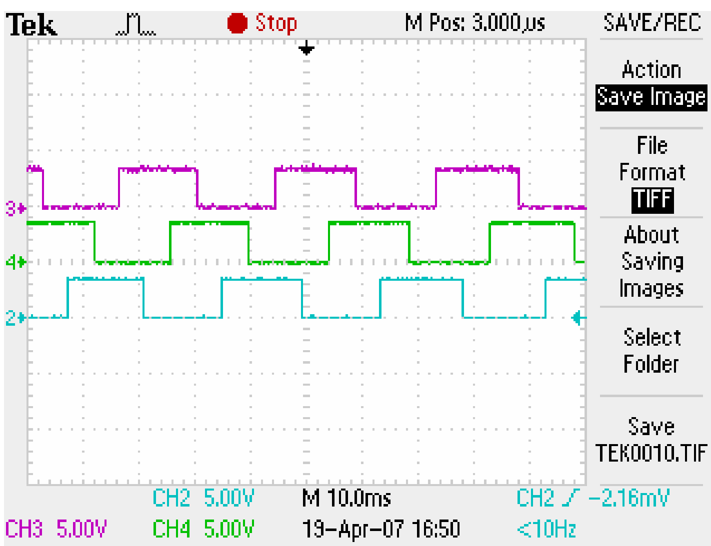

Fig.65 Obtained Hall Effect sensor output

5.6. Testing of inverter on Motor load

Then testing of the inverter circuit is carried out for the motor load. The maximum no load speed achieved on the no-load is 340 rpm at 90% duty cycle of the buck converter. Due to the noise in the output voltage of the inverter, ripple in the torque is obtained.

Table 6: Obtained speeds of motor for various duty cycles

Duty cycle	Obtained speed
90%	340 rpm
80%	295 rpm
70%	245 rpm
60%	200 rpm

Table 6. Shows that by varying the duty cycle from 60% to 90%, speed can be controlled from 200 rpm to 340 rpm.

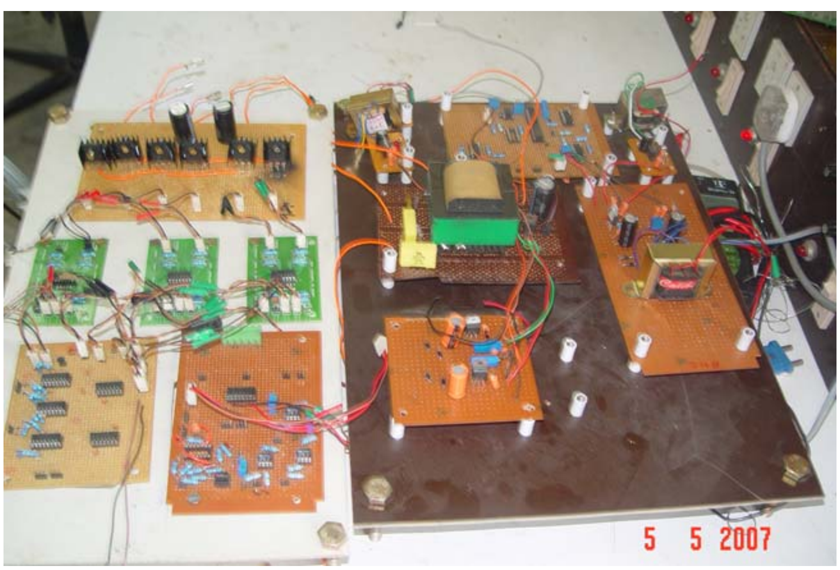

Fig.66 Development of buck converter & inverter

Fig.67 Complete set up of the project

Figure 66. Shows the development of buck converter & inverter portion of the project. & Fig.67 shows the complete set up of the project along with the PM Brushless DC Motor.

Chapter-6

MAJOR CONCLUSIONS & SCOPE OF FURTHER WORK

6.1. Major Conclusions

- PM Brushless DC Motor is the most preferable candidate for EVs, because of high efficiency, long operating life, and high dynamic response, better speed V/S torque characteristics, high speed ranges, noiseless operation, and rugged construction.

- Speed of the motor is controlled by varying the d.c. link voltage of the inverter, with the help of the buck converter. In buck converter, by selecting of the value of inductor 2.09 mH & capacitor of 1.5µF, satisfies the allowable current & voltage ripples of 1%. Output voltage of the buck converter is varied from 0 to 32 volt, by varying the duty cycle from 0 to 90%.

- Simulation results shows that no-load speed of the motor is controlled from 85 rpm to 760 rpm, by varying the duty cycle of 10% to 90%. While for the constant torque load of 0.1 N-m, speed of the motor is controlled up to 560 rpm, by varying the duty cycle of buck converter from 40% to 90%. So, range of the accelerator signal should be set between 40% & 90% of the full voltage.

- Inverter module is tested on the resistive load of the 10Ω. DC Link voltage of the inverter is varied from 12 to 36 volt by buck converter & obtained rms values of the output voltages are from 8 volt to 24 volt.

- By implementing this control strategy, maximum speed of the motor achieved for no-load is 340 rpm for 90% duty cycle. By varying the duty cycle from 60% to 90%, range of the speed obtained between 200 rpm to 340 rpm. Due to the noise in the output voltage of the inverter, pulsation of torque is obtained.

6.2. Scope of further work

- By filtering the noise in the output of the inverter of the drive, speed of the motor can further increased. & ripples in the torque can be reduced.
- Elimination of the dead time effects in the three phase inverter can further reduce the ripples in the torque & increase the speed of the motor, because dead time generates a decrease in the magnitude voltage of the harmonic fundamental and an increase in the low order harmonics.
- DSP based control makes the system response faster & reliable.

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Appendix

- Type of the Motor: PM Brushless DC HUB Motor
- Rating of the motor:

  Battery voltage= 36v,

  Rated speed=195 rpm,

  Power rating=250 watt,

  No. of poles= 40.