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Implementation of LC Filter in Torque Ripple Minimization of Sensorless BLDC Motor

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Abstract— *This paper presents the analysis, design and implementation of cost effective sensorless control scheme of Brushless DC Motors (BLDCM). There are several methods proposed in BLDC motor drives to obtain optimum current and torque control with minimum torque pulsation. But while coming to industrial applications, BLDC motor voltage contains harmonics which are caused because of high speed switching circuits resulting in high electromagnetic interference problems. During commutation pulsation torque is produced in the motor which are occurred by trapezoidal current pass through each phase. Here a cost effective methodology is implemented to reduce high frequency harmonics components and torque ripple using a LC filter. Here LC filter is connected at the input of the motor and hence the current waveforms are smoothened by the filter during the operation.*

Keywords—Brushless DC Motor (BLDCM), Electro-Magnetic Interference (EMI), Zero Volt Switching (ZVS), Zero Current Switching (ZCS), Total Harmonic Distortion (THD).

I. INTRODUCTION

The brushless dc motor (BLDCM) has found to be more efficient than the existing DC motor and induction motors Due to the simplicity in control scheme, high power density, reliability, and maintenance free operation, BLDC motors are used in the field of industrial automation, Computer numerical control machines and in the field of robotics. The mechanical losses are minimized since no brushes and no mechanical commutator present in the motor. The dynamics for this motor should be smooth for many industrial and automation applications. Due to the power electronic commutation, the usage of high frequency switching of power devices, imperfections in the stator and the associated control system, the input supply voltage to the motor contains various harmonics components. During its operation, high frequency components present in the voltage input will cause serious electromagnet interference (EMI) problem and the pulsating current input due to electronic commutation causes torque ripple. So an efficient controller is required to reduce the harmonics present in the input voltage to the motor and to reduce the pulsating variation of line current to the motor.

Now a days researchers are trying to reduce the torque ripple and harmonics component in the BLDC motor. The invention of BLDC motors brought a new topology in the applications of the motors. At beginning a microcontroller based topology was implemented on the control strategy of BLDC motors [1] this paper implements a micro controller based commutation control of the motor. A four quadrant sensorless control method is implemented on the suspension control method of motor control is discussed in [2]. An new approach of position sensorless drive for BLDC motor is discussed [3]. Here position sensors are implemented instead of hall sensors making it sensorless control for getting the feedback of the motor in controlling it properly.

A method for obtaining wide speed of operation in different speed ranges is brought [4]. Here indirect sensing for rotor flux position of permanent magnet AC motors is implemented. [5] describes the method implementing a new algorithm of sensorless operation of permanent magnet motors of hybrid commutation. A hardware polynomial based field oriented control of synchronous and asynchronous drives without mechanical sensor using a kalman filter is described on paper [6].

The resonant converters are having higher complexity in controllers and uses additional components to employ ZVS and ZCS to enhance the performance of the inverter and increase the efficiency.

This paper describes the implementation of a controller with minimized torque ripple and EMI effects using a filter placed at the input of the BLDC motor. The design of the filter components and the methodology of reduction of harmonics components are simulated and verified in real time application [7] [8].

The BLDCM is energized by the three phase inverter through an inductor - capacitor filter for reducing the high frequency component. The capacitor voltage value has to be selected in such a way that it can charge and discharge in an effective manner to reduce the high frequency component. The inductor present in series with each phase will reduce the commutation current pulsation and thereby reducing the jerk produced by commutation effects. Position controlled permanent excited synchronous motor without mechanical sensors [10] helps in reducing the cost. A design and implementation of an extended Kalman filter for the state estimation of a permanent magnet synchronous motor helps in rotor position estimation cost effectively [11].

The paper deals with implementation of hardware in sensorless control of brushless DC motor in minimizing the harmonics caused by torque ripple in the system. Here a LC filter is introduced between inverter and input of the motor. For the proper commutation and control of the BLDC motor an FPGA controller is used in it. The output waveforms are debited in this chapter. Along with connecting the filters to minimize the torque ripple, sensorless control of BLDC motors are also carried out here. This work describes a position sensorless operation of BLDC motor. The position sensorless BLDC drive proposed, in this work, is based on detection of back electromotive force zero crossing from the terminal voltages. The proposed method relies on a difference of line voltages measured at the terminals of the motor. It is shown, in the hardware that this difference of line voltages provides an amplified version of an appropriate back EMF at its zero crossings. The commutation signals are obtained without the motor neutral voltage. The effectiveness of the proposed method is demonstrated through experimental results.

II. SELECTION OF FILTERS

This design note is intended to be a design guideline and describes the steps to design a simple LC filter aimed to reduce the fundamental output ripple of our DC/DC modules. Other parameter such as cost, component availability and size should also be taken in consideration when designing the filter. The first step is to choose an inductor. The current rating of the inductor has to be equal to or larger than the maximum output current of the converter. The inductor must not be saturated. If the inductor saturates the inductance will decrease and the output ripple will increase. The next step is to choose a capacitor. The aim here is to select a capacitor with as high a value as possible with considerations taken to voltage ratings, size, cost and dynamic response. The added cost, for choosing a higher value of the capacitance than the minimum required, is usually compensated for by the enhanced performance, in terms of ripple and dynamic load response, of the filter and should be considered when selecting components. The following equation is used to calculate the required values of the filter components in order to achieve the desired damping ratio: LC filter design The LC filter consists of an inductor and a capacitor connected as follow.

Minimum required damping of the filter =

$$\frac{V_{maxripple}}{V_{Oac}} = \frac{X_c}{X_c + X_l}$$

Where

= Maximum allowed output ripple of the filter

= Listed output ripple of the filter of the DC/DC converter

$$X_L = 2\pi fL\ [\Omega]$$

Where

f = switching frequency of the DC/DC converter

C= Capacitance

L= Inductance

Determining the value of the filter components is a process of trial and error and may require a few calculations to optimize the LC filter. Another thing to consider is the LC filter resonant top that is created at the cut off frequency. The resonant top must be damped to not affect the stability of the converter. By putting a resistor in parallel with the inductor, the damping of the resonant to can be made. The value of the resistor can be equal as the impedance of the inductor.

III. BLOCK DIAGRAM OF PROPOSED SYSTEM

The block diagram for hardware setup shown in the Figure 5.1. The single phase 230 volt AC supply is fed to the rectifier. It is converted into DC using the rectifier and fed as input to the system. The dc supply is fed to the IGBT fed inverter via FPGA controller. The controller gives proper commutation to the inverter circuit via buffer IC's. Here LC filter is connected between BLDC motor input and inverter output. Here the back EMF is detected and fed to the controller with the help of current sensors connected in the system. After detecting the back EMF they are compared with the triangular waveforms and hence help in making PWM signals which are essential in making proper commutation in the motor. At sensorless mode with the detection of back

EMF the motor tends to start and after getting a proper start, it is switched over to sensorless mode where the motor runs at its rated speed. At conduction mode the current utilized by the motor is high resulting in high load current, which seems to be a disadvantage in this system.

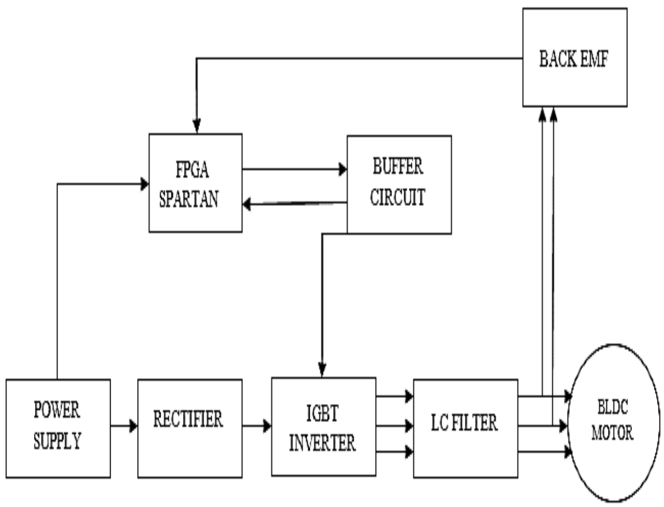

Figure 1 Block Diagram of the Hardware Setup

IV. CIRCUIT DIAGRAM AND OPERATION

The ac source voltage is converted into dc using the diode rectifier. The output of rectifier is fed to inverter. In this reduced switches topology each is placed across each dc source from the rectifier. Since the switches are working in a high voltage and current the processor and the driving IC's are not able to withstand that much amount of higher voltages so we are connecting it through an optisolator. In the controller the port B and port C is been initialized and the delay timings is been given by assigning the proper conditions for the processor. The input to the inverter is been given through the BLDC motor.

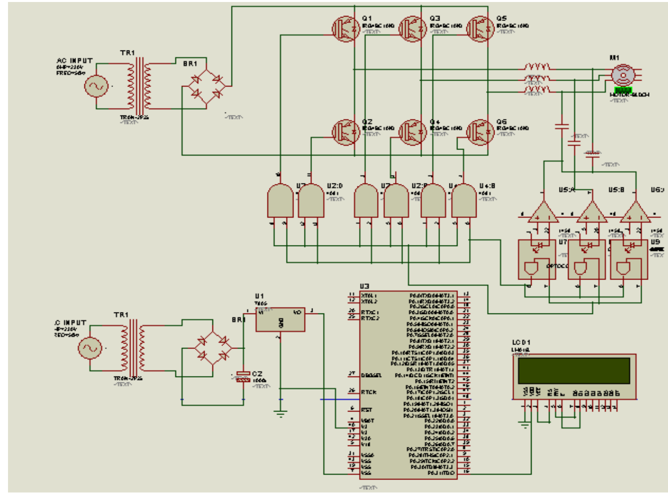

Figure 2 Hardware Circuit Diagram

The circuit diagram of motor and controller part is shown over here, consisting of current sensors and voltage sensors, to detect the back EMF and to produce PWM signals for the proper commutation of the motor. From this circuit diagram the LC filter are connected in between the input to the motor and the output of the inverter. Controller are connected to the inverter via buffer IC's in enhancing the signals and in making proper commutation of the motor. With the help of FPGA, the current commutation in the system is maintained properly by obtaining the back EMF signals of the motor which are running at sensorless mode.

Table 1 BLDC Motor Specifications

Parameters	Values
Power Ratings	60W
Voltage Ratings	24VDC
Rated Speed	3000RPM
SR.NO	02.13.1331
Product of	Tachometric Controls

V. HARDWARE RESULTS

This work proposes an improved methodology to reduce the high frequency harmonics components and torque ripples using a LC filter connected at the input of the motor and a position sensorless operation of permanent magnet brushless direct current motor also done. An experimental setup is developed to analyze the performance of the drive with the proposed system and the experimental outputs were compared with the simulated values and the improvement in performance is analyzed. Here the voltage waveforms are taken and these waveforms are compared with the waveforms taken with the filter and without the filter. After that waveforms regarding the sensorless modes are taken which consist of back EMF waveforms which are obtained at 120o conduction mode and sensorless mode. At sensorless modes the current and voltage waveforms are taken and compared with each other. With the results the working of motor is explained that how it is running without sensors even if they are not self-starting motors. It is clear from the results that sine waves are compared with the triangular waves and a zero crossing point is obtained and at this point the FPGA's produces appropriate pulses which are essential for proper commutation of the motor to run properly

A . Voltage Waveform of BLDC Motor without a LC Filter

The output waveform of a brushless dc motor without connecting a LC filter is shown in the Figure 5.9. Here it is observed that torque ripple is produced in the voltage waveforms which are caused because of internal harmonics. As torque are produced as a after effects of a rotatory motion. The Figure 10 represents a current in terms of voltage waveforms which are taken at precision power analyzers. Here the LC filters are used in reducing the torque ripple in system, it is clear from the waveforms obtained in the Figure 3that the system is having some ripple in it.

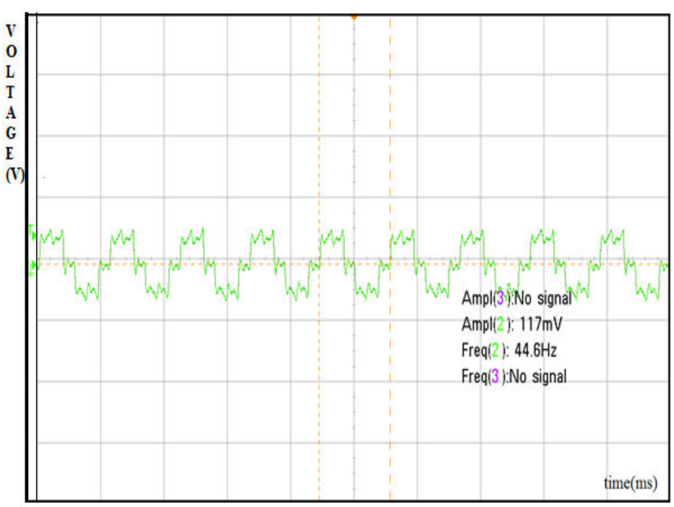

Figure 3 Voltage Waveform of BLDC Motor without Using LC Filter

As the BLDC motors are excited with an trapezoidal input but from the figure it is clear that ripples are presented in the system and these ripple results in harmonics of the system, affecting the efficiency and performance of the motor to run at it full effect. Thus it is to be minimized in making to run the motor at its full efficiency, a LC filter is introduced at the proposed system where they helps in reducing the harmonics of the motor running at rated speeds.

The analyzer are connected in between inverter output and BLDC motor input where they are connected across using resistors across it inorded to protect the circuitry from other hazards. From the voltage waveforms it is clear that it definitely having some harmonics. Here in this proposed system LC filters are introduced in reducing the harmonics and at the same time sensorless control of the motor is made using back EMF detection technique. Thus from the Figure 4it is clear that harmonics are produced at the voltage waveforms.

B. Sensorless Control of BLDC motor

This work proposes a simple and reliable method for the detection of back EMF zero-crossings for sensorless operation. Here, the zero crossings of the back EMF are estimated indirectly from the terminal voltages measured with respect to dc negative terminal. The method does not involve any integrations. Further, since line voltages are used, the requirement of neutral potential has been eliminated. This also eliminates the common mode noise. Device drops and their variations would also not play a part since line voltages are used. Unlike the method described in the scheme is easy to implement. No derivative operations are involved. In the approach to zero- crossing detection was used to reliably start the BLDC machine in sensorless operation. In this work, the approach is extended to propose a simple running mode algorithm. Here on Figure 4zero crossing of back EMF is shown and the shaded part shows the switching of the system where two switches are in ON state and one in OFF state. From this zero crossing point FPGA's produces proper pulses for exciting the motor.

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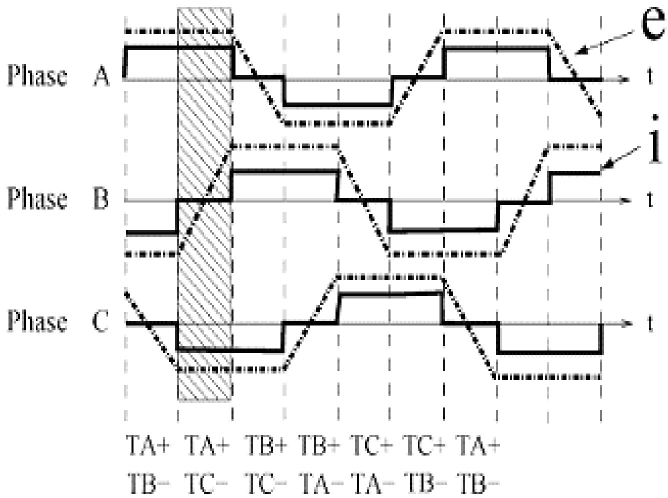

Figure 4 Zero Crossing of Back EMF

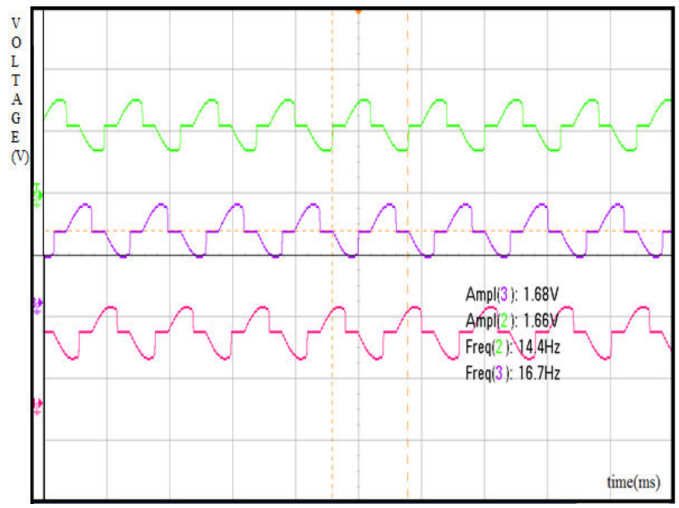

Figure 5 Waveform at 120 Degree Conduction Mode

C Waveforms at 120 Degree Conduction Mode

Consider a BLDC motor having three stator phase windings connected in star. Permanent magnets are mounted on the rotor. The BLDC motor is driven by a three phase inverter in which the devices are triggered with respect to the rotor position as shown in Figure 5 The 120 degree conduction mode waveform is shown in Figure 5here the voltage waveforms at three phases is obtained. These waveforms are made up of comparing sine signals with triangular waveforms and hence this technique is known as sine PWM technique.

The back EMF along with current of phase B during starting and running modes is shown in here. It is evident that the commutations are performed at the ZCPs in the starting mode, whereas in the running mode, it is in phase with the flat portion of the back EMF. Subsequent to the changeover, 60^o interval detection and the delay of 30o is performed on a continuous basis to maintain operation in the running mode. At this mode the current taken by the load is very high, thus they are recommended only for starting purpose of motor, as BLDC are not self-starting motors.

Consider the interval when phases A and C are conducting and phase B is open as indicated by the shaded region in Figure 6. In this interval, phase A winding is connected to the positive terminal of the dc supply, phase C to the negative terminal of the dc supply and phase B is open. Therefore, i_a= -i_c and i_b = 0. It can be seen from Figure 7(shaded region) that the back EMF in phases A and C are equal and opposite.

The difference of line voltages waveform is, thus, an inverted representation of the back EMF waveform. The EMF values would be those in a resistance, inductance, EMF representation of the phase which is not referred to ground. It may also be noted that the subtraction operation provides a gain of two to the EMF waveform thus amplifying it. It is again evident from Figure 5that during this interval (shaded portion) the back EMF e_{bn} transits from one polarity to another crossing zero. Therefore, the operation $V_{ab}- V_{bc}$ (V_{abbc}) enables detection of the zero crossing of the phase B EMF. Similarly, the difference of line voltages V_{bcca} enables the detection of zero crossing of phase C back EMF when phase B and C back EMFs are equal and opposite. The difference of line voltages V_{caab} waveform gives the zero crossing of phase A back EMF where phases C and B have equal and opposite back EMFs. Therefore, the zero-crossing instants of the back EMF waveforms may be estimated indirectly from measurements of only the three terminal voltages of the motor.

D 120 Degree Conduction Mode to Sensorless Mode Waveforms

The proposed sensorless method is done by coordinating with EMF zero crossing detection method. The functional sequence of operations of the proposed back EMF zero-crossing detection for sensorless operation is shown in Figure 6, and is further explained in the following. From the sensed terminal voltages with respect to negative dc bus (V_a , V_b , V_c), line voltages, and subsequently their differences (V_{caab} , V_{abbc} , V_{bcca}) are determined. Figure 7shows the back EMF waveform of phase B and the line voltage difference V_{abbc}. The sensorless commutation instants are delayed by 30^o electrical degrees from the back EMF zero-crossing instants in order to excite the phase windings during the flat portion of the back EMF

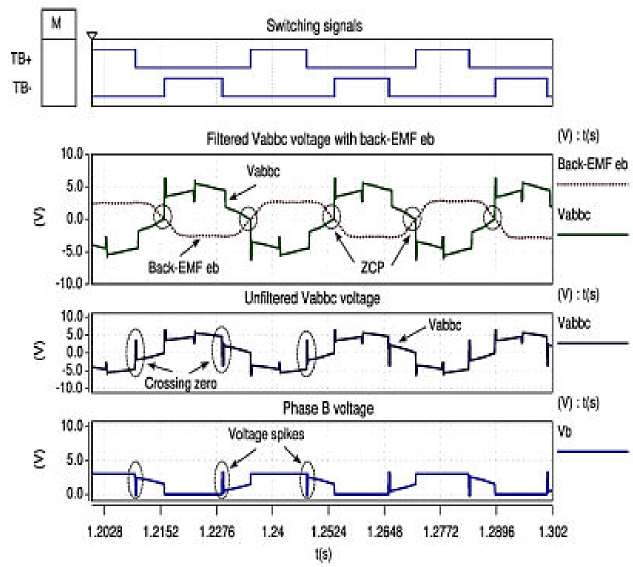

Figure 6 Detection of Back EMF Zero Crossing

These are indicated as zero-crossing points (ZCP) in Figure 7 It can be seen that the plot validates in This waveform contains spikes due to free-wheeling diode conduction. When the line the region of zero crossing of the back EMF. Figure 7also shows the terminal voltage Vb of phase B. voltage difference, say V_{abbc} is found, these spikes cause false zero-crossing detection, and hence need to be eliminated. This is done by holding the value of the terminal voltage before spike occurrence for a predetermined duration.

Once the motor is started in the sensorless starting mode, then the correct commutation instants are to be estimated from the ZCP in order to switch over to running mode. The sensorless commutation instants are delayed by 30^o electrical degrees from the back EMF zero-crossing instants in order to excite the phase windings during the flat portion of the back EMF. This is done as follows. When the motor is in the sensorless starting mode, a 12-bit digital counter is started at a zero-crossing instant of the back EMF. Zero crossings occur every 60o electrical degrees of the rotor rotation. The timer is stopped at the subsequent zero-crossing instant. Thus, the duration of a 60o interval is established. Half of this time interval, which is 30^o, is obtained by a right shift of the counted value by 1 bit, and then it is loaded into a digital comparator.

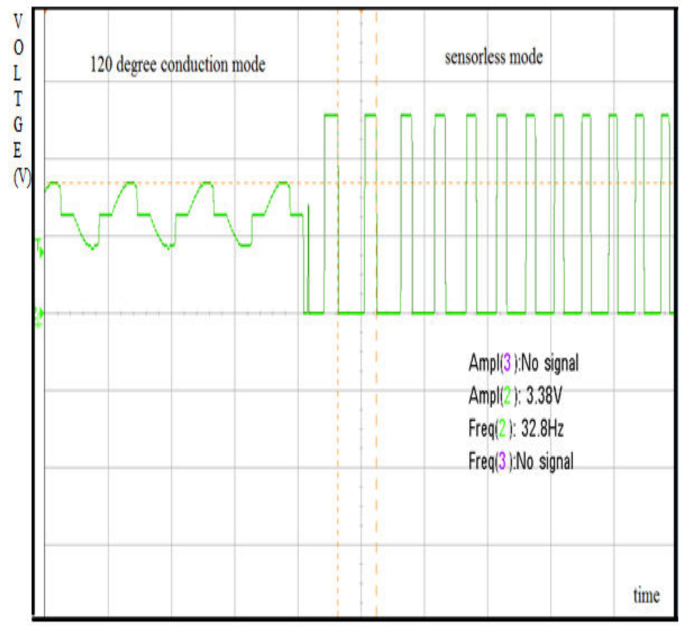

Figure 7 At 120 Degree Conduction Mode to Sensorless Mode Waveform

E Voltage Waveform of BLDC Motor after Connecting LC Filter

Here the LC filters are used in reducing the torque ripple in system, it is clear from the waveforms obtained in the Figure 5.15. From the waveforms taken from the Figure 5.19, it can be observed that the voltage waveforms are having ripple, in which they are caused by internal harmonics in the system. In reducing these harmonics an LC filter of having inductance value 0.1mH and capacitance having 0.01μF. The three phase voltages at any particular instant are shown in three colored waveform. From the comparison of the figures obtained while running the motor with the filter and without the filter are shown and compared. From the comparisons it is clear that the ripple is minimized by the use of filters cost effectively and can be conclude they are the one of cheapest means in minimizing the harmonics. Figure 3shows the harmonics present in the phase-A of the voltage to the motor. The harmonics are present in the switching frequency of the power devices and the multiples of switching frequencies.

Figure 8 shows the combined waveform for the three phase current input to the motor. From the figure it expresses the currents in different phases of the motor. The profile of the current is been transferred from distorted trapezoidal profile to somewhat clear trapezoidal profile by the help of filter. This improves the commutation effect of the motor. The drastic variation of the current in each phases are smoothened by the filter. This minimizes the commutation losses of the drive and minimizes the torque ripple

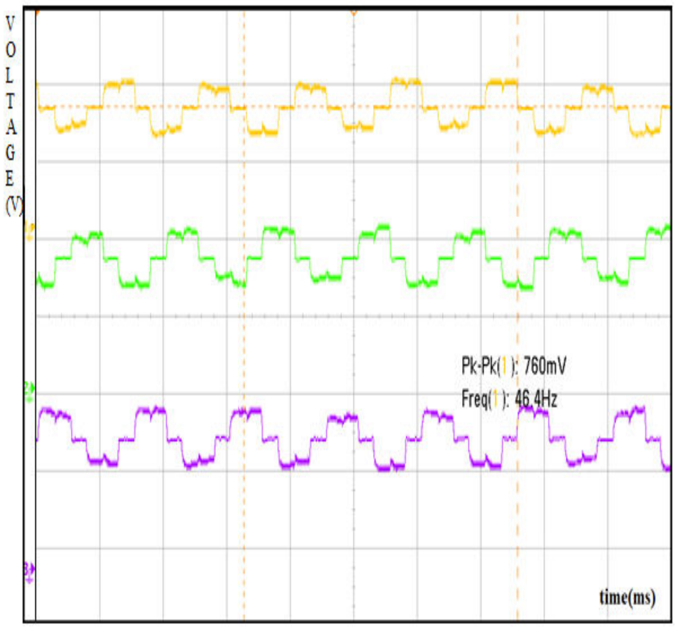

Figure 8 Voltage Waveforms after Connecting LC Filter

The hardware setup of the proposed system is shown in the Figure 9. Where the setup consisting of sensorless control of brushless dc motor where n LC filter is used in orded to minimize the torque ripple caused in the system.

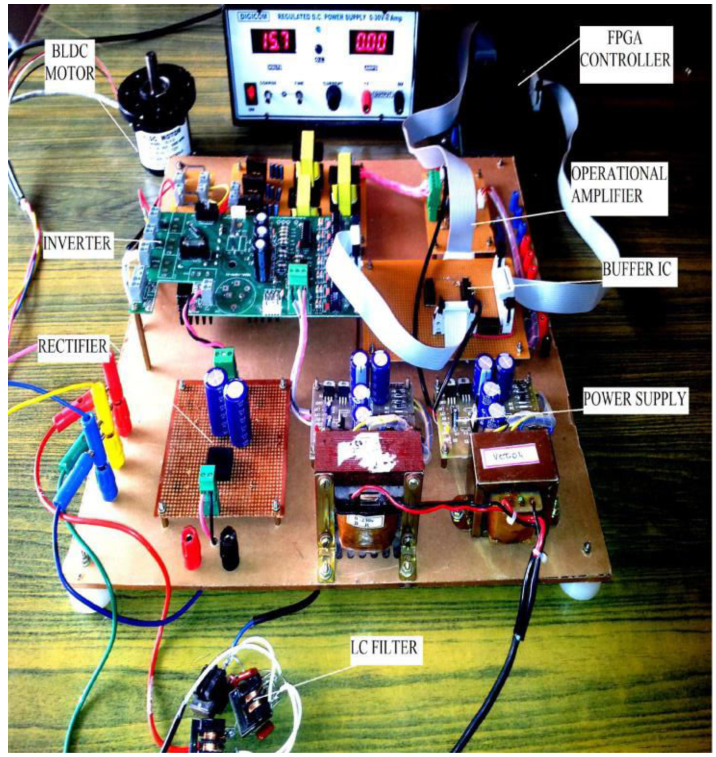

Figure 9 Hardware Setup

VI. CONCLUSION

In this project the harmonics content of the voltage and current for a BLDC motor is analyzed. From the simulated results it is evident that the harmonics components at the switching frequency and multiples of switching frequency are reduce by the filter. From the experimental results, it is found that up to a very good extent the harmonics components are reduced with filter. The current waveforms are smoothened by the filter during the operation and the commutation frequency harmonics minimized and thereby the torque ripple is reduced

It is concluded that, it is possible to obtain precise speed control of BLDC motor using an LC filter. Again here the use of a sensor is not implemented for the speed control of the system, instead of that a sensorless control technique is implemented in order to get the stator and rotor position of the system. The sensorless part of the system is done by using back EMF detection technique where the back EMF of the motor is detected with the help of filters and from these signals a sine wave is obtained and they are compared with the triangular waveforms with the help of controllers. A simple technique of detect back EMF zero crossing for a BLDC motor using line voltages is proposed. It is shown that the method provides a amplified version of the back EMF. Only three voltage terminals need to be measured thus eliminating the need for motor neutral voltage. While starting relies on triggering devices at zero crossing detection algorithm, continues running is achieved by realizing the correct commutation instants 30o delay from the zero crossing. The motor is found to start smoothly and run sensorless even with the load and load transients. Hence a sensorless control of motor is made for precise running of the motor. This project presents the development of a LC filters specially designed for reducing the harmonics of the motor along with sensorless control of brushless DC motor where the simulation and experimental results validate suitability of the proposed method .

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