DEVELOPMENT OF A COST EFFECTIVE POWER CONTROL UNIT FOR HYBRID ELECTRIC VEHICLE DRIVE

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ABSTRACT *—In recent years, world has moved towards green and renewable energy resources. Transport sector is also switching towards zero emission vehicles such as electric vehicles (EV). Despite the speedy progress of green vehicle markets, its machineries including power control units (PCUs) are still very expensive as compared to the similar products of conventional vehicles. A development in integration technology is needed to reduce the costs and save more spacing in the electric vehicles. This paper proposes the design and development of PCU for hybrid/ electric vehicle. In this regard, a novel topology has been introduced to design a cheap, compact and efficient power control unit for three wheeler light electric vehicle (Auto Rickshaw). An inexpensive PCU is subsequently designed using facilities and components readily available in Pakistani market. It has the ability to control upto 10 HP traction motor based auto rickshaw carrying two passengers with maximum speed limit of 40 kph on a slope upto 15 degrees. Simulations and experiments results are compared to verify the strength and the performance of designed PCU.*

Index Terms — Power Control Unit, Electric Vehicle, Power Electronics, Renewable Energy.

I. INTRODUCTION

Transportation sector in Pakistan is the main consumer of imported hyadrocarbon oil which causes huge drain in the economy of the Pakistan [1]. Due to lack of technical expertise in the automotive industry [2], an effort is being made by the Pakistani Government in taking an interest in automotive industry development. Under these circumstances, it is desirable to reduce the import of oil and replace conventional vehicles with hybrid and pure electric vehicles. Government of Pakistan, especially Punjab Government, is interested in the development of local hybrid/ electric vehicle (HEV)/EV industry for light and mild vehicles. Three wheeler auto rickshaw is one of the most common light vehicle used for public transport within urban areas of Pakistan. The Punjab Government aims to replace the conventional auto ricksaws with pure and hybrid EVs to reduce the oil usage and environmental pollutions. Figure 1 shows the oil consumption in Pakistan divided by consuming sectors [3].

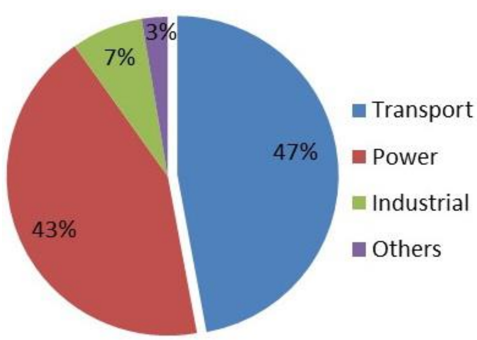

Figure 1: Oil consumption in Pakistan by sectors [3]

The HEV/EV industry is heading towards a 48V system by replacing old topologies of high voltage systems. This modification will allow the HEV/EV to use small size traction motor rated around 10KW which may be able to utilize the regenerative braking technique to save the energy being wasted by brakes resulting in fuel efficiency improvement up to 17% [4]. Such systems will also be beneficial in terms of HVAC systems in HEV/EV [5]. Unfortunately, Pakistan has no industry related to HEV/EVs. Batteries commonly used in HEV/EV are NiMH or Li-ion [6], and are not available in Pakistan for automotive applications. The components of HEV/EV like power control units, battery banks and motors are not being manufactured in Pakistan to-date. This paper introduces a simple topology for three wheeler auto rickshaw EV.

Power control unit is a power electronics device which is used to control torque and speed of the motor [7]. Generally it has a three phase inverter, a DC-DC converter and real time controller [8]. In this paper a power control unit is designed for three wheeler light electric vehicle using local market facilities. Used or repaired PCUs of Toyota Prius are available at a proce of approximately 16000 PKR from brake-yards, however, new PCU is not available in the market. It could be imported from advanced countries like Japan which is way more expensive. Reduction of price is always of primary concern for any development. However size reduction and less weight are also being considered.

Rest of the paper includes theoretical study leading towards simulations and practical manufacturing of the power control unit. Simulations are tested and verified and then PCBs are designed for a compact PCU design.

II. MODELING & ANALYSIS

A. Overview of existing topology

A typically common topology being used in hybrid electric vehicles is shown in Figure 2[9]. Low voltage and high voltage bus bars are used to transmit power. Low voltage battery banks are connected to low voltage bus bar. Power is fed to bidirectional DC-DC converter which steps it up behaving as a boost converter resulting in high voltage output. High voltage is provided to inverter which converts the high voltage DC into high voltage three phase AC. This three phase AC power energizes the traction motor. This whole process is shown in Figure 3(a).

When brakes are applied, motor behaves as a generator and produces three phase AC power by regenerative braking technique. This AC power is fed to inverter which acts as a

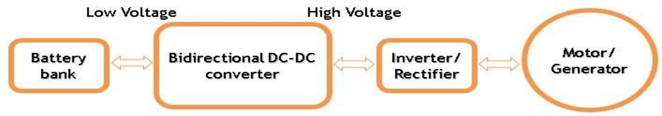

Figure 2: Commonly used topology in HEVs

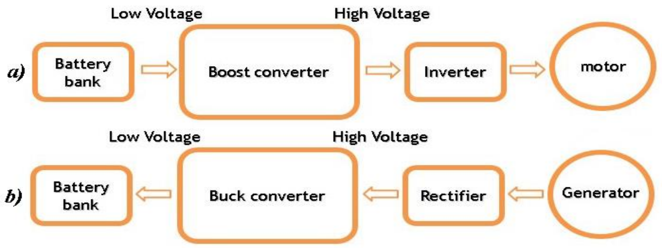

Figure 3: Inverter and rectifier mode

rectifier. Rectifier converts the AC into DC and DC link capacitors filter the ripples of generated DC. Bidirectional DC-DC converter works as buck converter and saves that energy into battery bank for later use. Figure 3(b) shows the whole process of power generation and its storage into battery bank. Toyota Prius works on this topology [10]. Toyota Prius is very commonly used HEV worldwide. Its PCU is analyzed because of its availability in local market which also allowed for its price comparison.

B. Proposed new topology

In EV/HEV, high voltage levels are used when dense output power is required [11]. In this research three wheeler light EV is targeted which do not need high dense power. So the high voltage level approach is eliminated by rewinding the high voltage rated motor to low voltage level. It simply excludes the topology of two bus bars and bidirectional DC-DC converter in EV.

In this proposed topology, bidirectional DC-DC converter has been eliminated. It simplifies the PCU model and its controlling algorithm. It reduces PCU size, mass and cost. Its removal improved the overall efficiency of the power control unit. A block diagram of this proposed topology is shown in Figure 4.

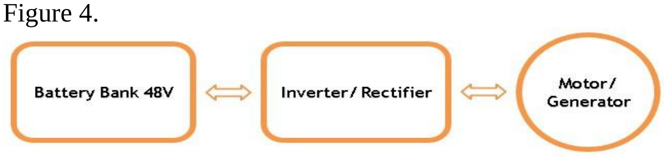

Figure 4: Proposed topology

When a traction motor needs electrical power from the battery bank, the three phase voltage source inverter converts the DC power into three phase AC power and feeds it to the motor. To utilize the regenerative braking power being generated by the traction motor (working as a generator), six diodes connected across each MOSFET of three phase inverter allows it to rectify the three phase input power into DC. That power is filtered using DC link capacitor and fed into the battery bank for later usage.

III. METHODOLOGY

We designed a PCU for 10HP traction motor, which might allow the auto rickshaw to travel at the maximum speed of 40 Km/hr carrying two passengers within the acceptable range of slopes.

Real time controller (Arduino Mega 2650) is used to deal with the inputs from the driver and respond accordingly. A toggle switch allowed the driver to choose between forward and reverse movement of the auto rickshaw. A potentiometer is installed in the handle of the auto rickshaw which allowed the driver to vary the acceleration using right hand to feel like the driving of conventional auto rickshaw.

Power control unit designing is done in two different parts: a control PCB, and a power PCB. The reason for this separation is to separate the high and low power circuitry. Simple two layers PCBs are developed for both cases as that is the only possible option available in the lab. An electronics design and simulation software Proteus from Labcenter Electronics is used for schematics, simulations and PCB designing. Figure 5 shows the block diagram of the PCU. 48V is the only power source used to energize the whole system. It provides power to real time controller as well as the three phase inverter.

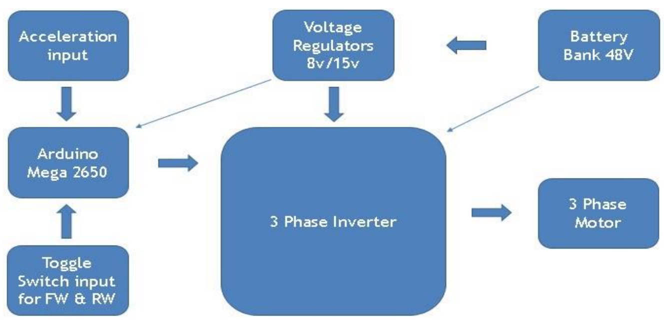

Figure 5: Block diagram of a PCU

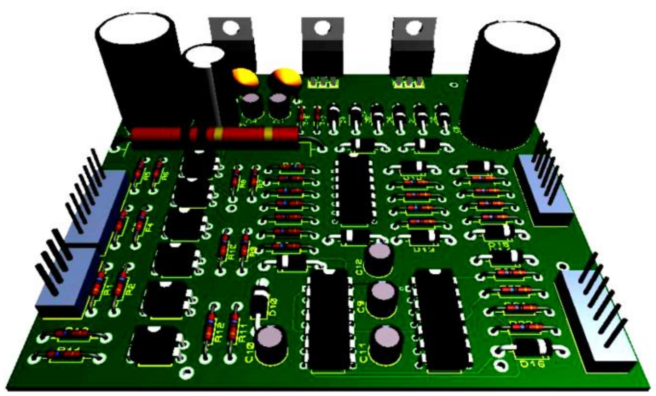

Figure 6: CAD view of a control PCB

A. Control PCB Components & Schematics

The control PCB has all the low voltage components which are required for the controlling of a power control unit. Figure 6 shows the CAD view of the control PCB designed in Proteus 8 professional. Control PCB is divided into three modules; Power Module, Isolation module and gate driver module. Details of each module is provided below.

Power Module: This block contains all the voltage regulators to provide regulated power supply for Arduino Mega 2560, gate drivers and isolation module. Zener diodes and capacitors are used for protection and filtration respectively. Diodes are placed to stop the chances of reverse current flow. Voltage regulators converts the battery bank voltage of 48V DC into 8V and 15V regulated supplies. 8V and 15V are supplied to Arduino Mega 2560 and gate driver module respectivily. One Transistor is used as a voltage regulator with two zener diodes (15V each) in series on its base to step down the input voltage of 48V to 18V DC. Then voltage regulator L7815 is used to get smooth 15V output and L7808 for 8V regulated output supply. The Schematics of power module is provided in Figure 7.

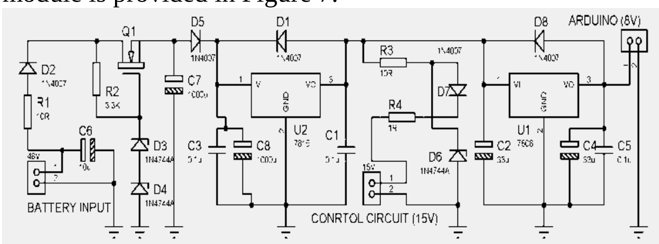

Figure 7: Schematics of Power Module

Isolation Module: This module isolates the controller (Arduino Mega 2560) from the whole power control unit. Secondary objective is to amplify the input signals coming from Arduino Mega 2560. Six PC817 optocouplers are used to isolate the gate signals coming from Arduino Mega 2560. Resistors are connected on both sides of optocouplers to limit the current flow. Optocouplers are energized with 15V DC coming from power module whereas Arduino is powered with 8V DC coming from the same source. The schematics of isolation module is shown in Figure 8.

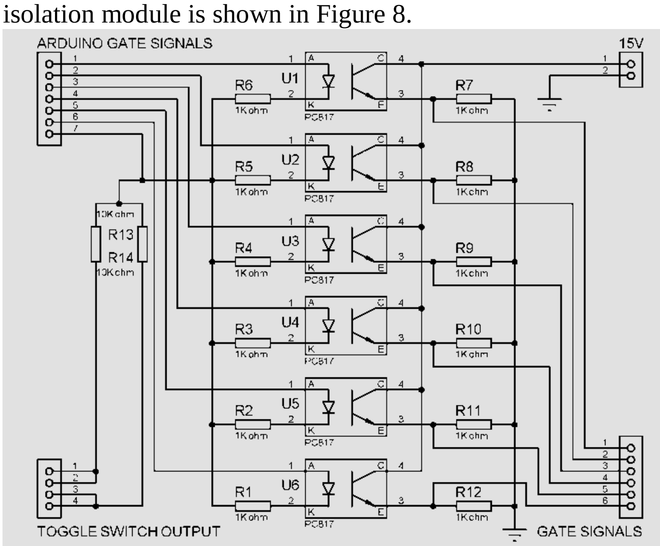

Figure 8: Schematics of Isolation Module

*Gate Driver Module:*This is the most important module of the control PCB. It has three gate driver ICs IR2110. Each gate driver is providing high and low side driving for each half bridge of inverter. The Arduino Mega 2560 input signals coming via optocouplers are fed to these gate drivers. Gate drivers are energized by 15V DC supply coming from power module. They supply boosted signals with high current to the gates of the MOSFETS. IR2110 restricts high and low side of inverter's leg to turn on at same time [12]. A bootstrap capacitor and diode are connected with the upper MOSFET of each leg. In order to have an independent controlling of MOSFETs, separate pulse width modulated signals are used for each MOSFET. The distance between gate driver and gates of the MOSFETs need to be as minimal as possible to avoid parasitic inductance. The inductance reduces the current which slows down the switching speed [13]. This phenomena can cause both MOSFETs of same leg to turn on at same time shorting the positive and negative supply of the battery resulting in spark and even fire catching [14]. The schematics of power module is provided in Figure 9.

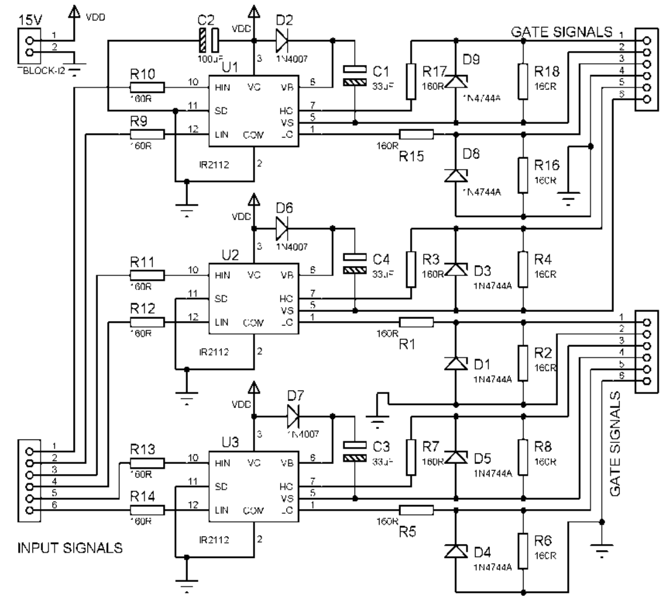

Figure 9: Schematics of Gate Driver Module

B. Power PCB Components & Schematics

The power PCB had all the high voltage components like MOSFETs based half bridges and DC link capacitors. Figure 10 shows the CAD view of the power PCB designed in Proteus 8 professional. Control PCB is divided into two modules; three sets of half bridges and DC link capacitors bank. Details of each module is provided below.

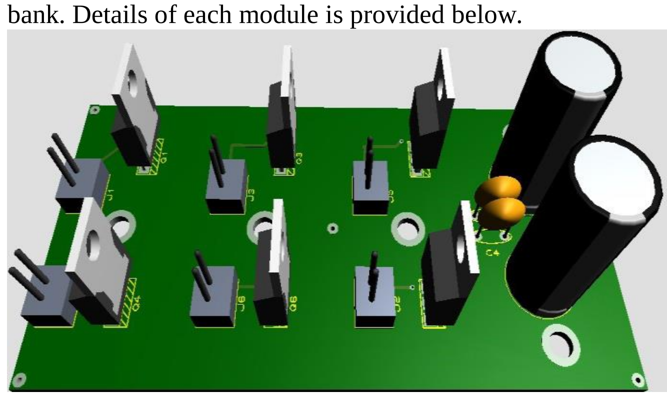

Figure 10: CAD view of a power PCB

Half Bridge Module: This module contains three half bridges. These three half bridges composes the three phase inverter. Each half bridge consisted of two MOSFETs, one for upper side and one for the lower side. Each pair of MOSFET is connected with one common gate driver IC. The MOSFET switching pattern is shown in the Table 1. There was a dead time between the switching of two MOSFETS to allow the current to free wheel through the diode.

Table 1: Switching Pattern of MOSFETS

State No.	T_1	T_2	T_3	T_4	T_5	T_6
1	ON	OFF	OFF	OFF	ON	ON
2	ON	ON	OFF	OFF	OFF	ON
3	ON	ON	ON	OFF	OFF	OFF

4	OFF	ON	ON	ON	OFF	OFF
5	OFF	OFF	ON	ON	ON	OFF
6	OFF	OFF	OFF	ON	ON	ON

DC link Capacitor Module

DC link capacitor bank consisting of six capacitors are connected in parallel with battery bank. The purpose of using two electrolytic capacitors is to filter the low frequency ripples and other four ceramic capacitors are used to filter the remaining high frequency voltage ripples. The minimum value of the electrolytic capacitor is calculated using

$$C_{min} = \frac{I_m}{\Delta V f_s} \qquad (1)$$

where I_m is the motor current at peak level, ΔV is the maximum acceptable voltage ripples and f_s is the switching frequency [15]. Schematics diagram of H bridge module along with dc link capacitors is shown in Figure 11.

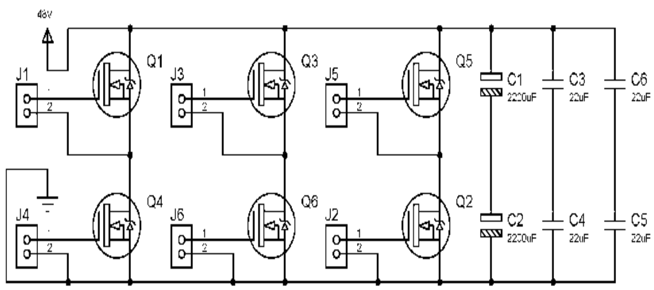

Figure 11: Schematics of a power PCB

IV. EXECUTION AND RESULTS

Multiple Pulse With modulation (MPWM) technique is used to control the duty cycle of the gate signals. Six gate signals are generated using Arduino Mega 2560. Figure 12 shows the gate signals waveforms with 100% duty cycle taken from the simulation on Proteus ISIS. Each gate signal has the phase delay of 60° from ascending or descending signal. Each pair of signals for any leg of three phase inverter has phase shift of 180°. Gate signal 1 and 4, 2 and 5 and 6 and 3 are pairs for 1st , 2nd and 3rd leg respectively.

Figure 13 shows the input gate signals of the PCU taken via oscilloscope. Figure 13(a) shows gate signal 1 and 4. It is pair for 1st leg of H bridge with phase difference of 180°. Due to the limititation of 2 channels of the oscilloscope, the comparison is done in multiple windows. Figure 12(b) shows gate signal 1 and 5. However, the last window (c) shows the gate signal 1 and 3.

Figure 14 shows the gate signals with varying duty cycles using multiple pulse width modulation. The reason for using this technique was its simplicity of implementation using Arduino as it has the built-in feature of MPWM. To vary the torque and speed of the traction motor, the acceleration is varied using potentiometer. Each window in figure 14 shows increased duty cycle with respect to the increase in frequency to maintain the V/F ratio constant up to certain level. When the duty cycle reaches 100%, the frequency is increased keeping voltage constant to increase the speed of the traction motor. Figure 15 shows the signal waveform with 100% duty

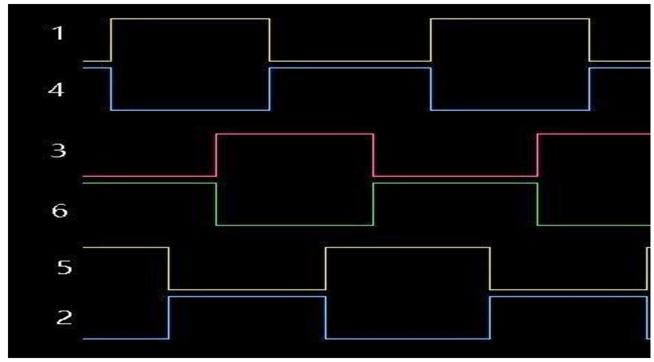

Figure 12: Gate signals with 100% duty cycle on a simulator

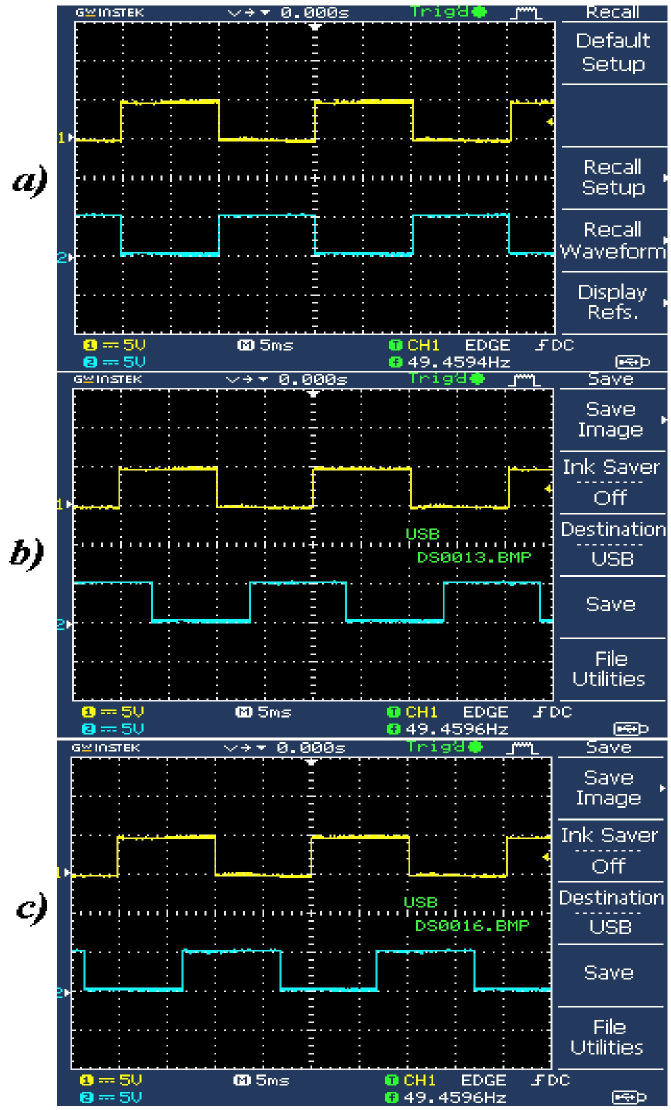

Figure 13: Gate signals generated with 100% duty cycle

cycle. Figure 15(a) and (b) signal waveforms have same duty cycle i.e. 100% but different frequencies.

PCU is designed in Proteus ISIS and simulation results are studied to verify the performance of the PCU within required specifications. .hex file generated by Arduino

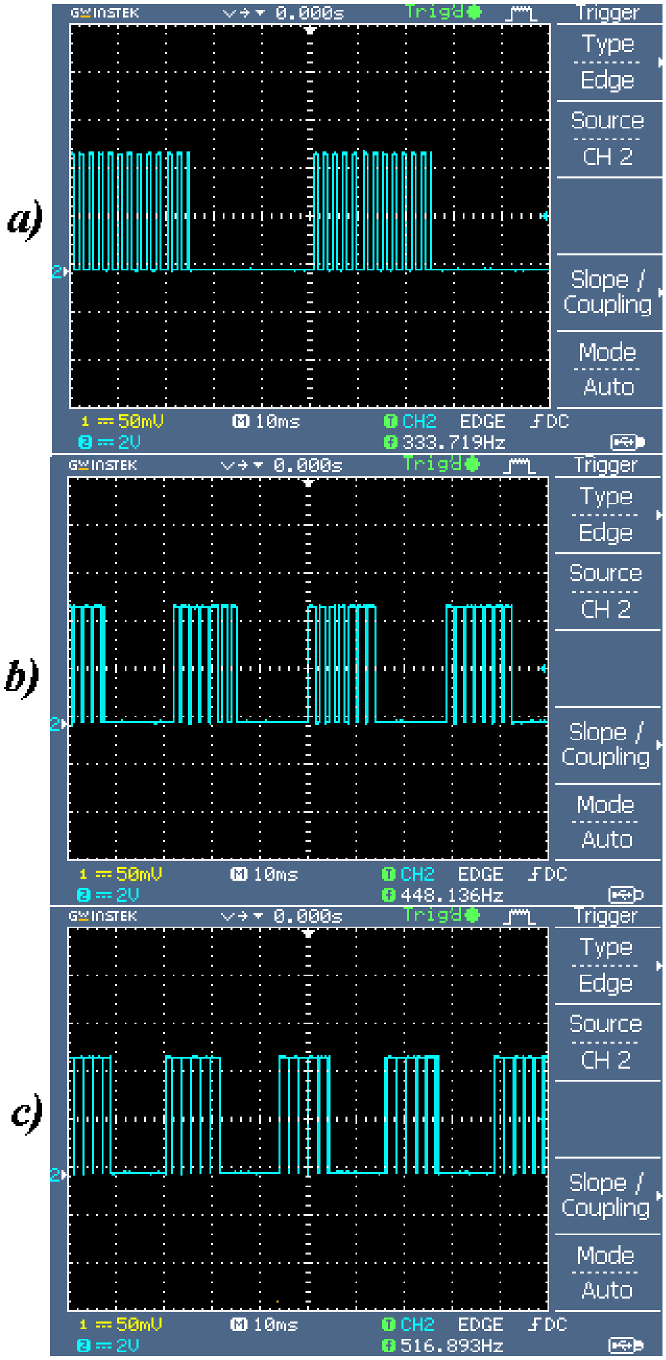

Figure 14: Gate signals with different duty cycles and frequencies

IDE is called in Proteus ISIS and these three phase output waveforms are produced. Figure 16 shows the simulated output line voltages waveforms of the PCU. Each color defines the separate phase number. Line voltages V_{ab}, V_{bc} and V_{ca} are shown in green, blue and red colors respectively. These output waveforms are overlapped in analogue analyzer of Proteus ISIS to verify the phase shifts between them. Figure 17 confirms the phase shift of 120° between every line voltage signal. After 360° cycle each signal is being repeated.

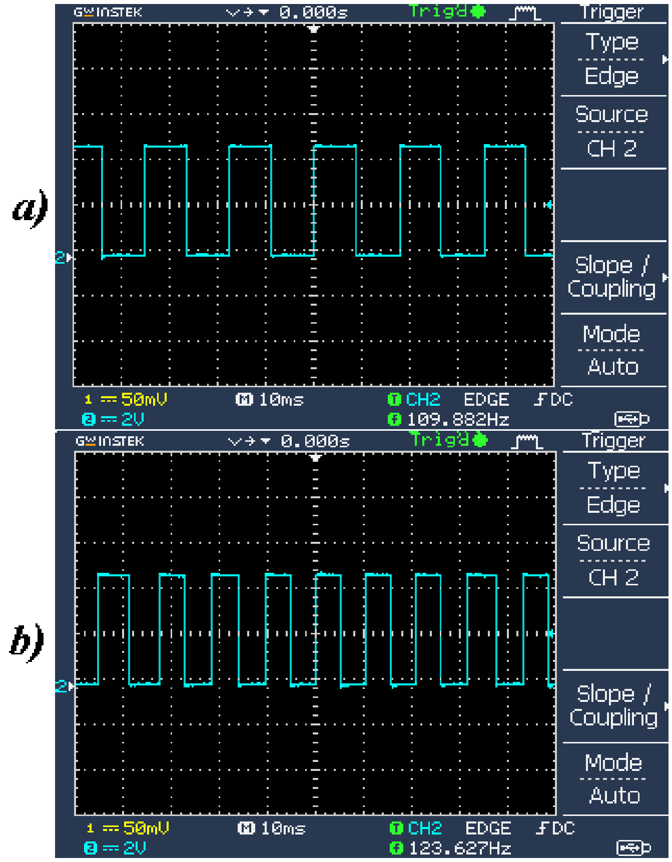

Figure 15: Gate signals with 100% duty cycle and higher frequencies

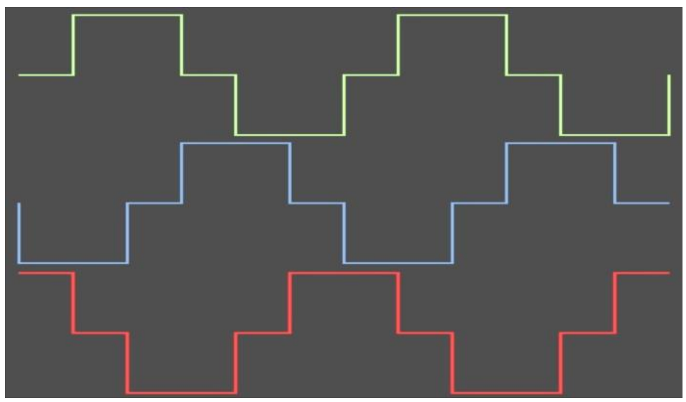

Figure 16: Simulated PCU output signals

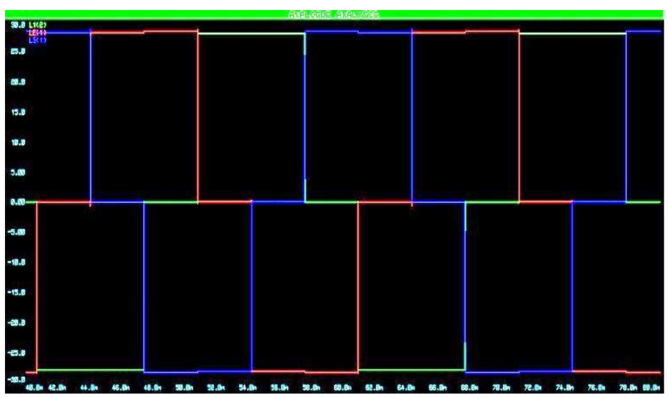

Figure 17: Output voltage signals overlapping in Simulator

After successful simulation results, the PCU prototype is designed and tested. Figure 18 shows the PCU generated signals of line voltages. In first window, V_{ab} and V_{bc} are shown while second window shows the wave forms of V_{ab} and V_{ca}. The phase shift of 120° can be seen between V_{ab} , V_{bc} and V_{ca}. Simulation and practical testing results are precisely matched.

a)

b)

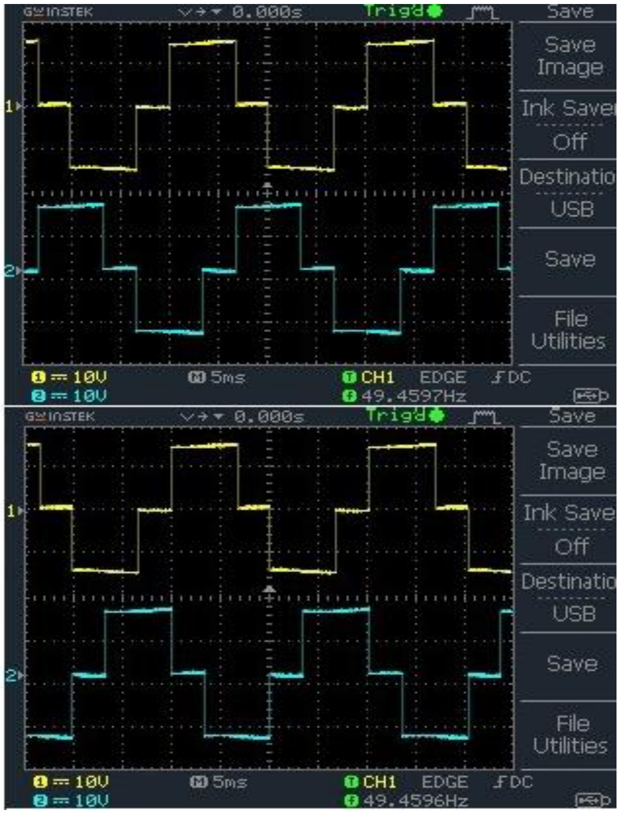

Figure 18: PCU output voltage waveforms (Practical results)

Table 2: Output Voltage levels against different duty cycles and frequencies

Duty Cycle (%)	Frequency (Hz)	V_{ab} (V)	V_{bc} (V)	V_{ca} (V)
20	10	6.78	6.77	6.78
50	25	17.01	16.98	16.99
80	40	27.16	27.18	27.16
100	50	33.94	33.96	34.01
100	150	33.91	33.94	33.99
100	175	33.99	34.06	34.02
100	200	33.97	33.98	34.00

A rough hardware is designed to test the controller and circuitry of the desired PCU. It is successfully tested with 3KW Induction motor installed in Auto Rickshaw. The designed PCU is tested on different frequency levels to confirm its functionality. It resulted in desired outputs. Table 2 describes the test results briefly. Figure 19 shows the designed hardware prototype. Whereas Figure 20 shows the auto rickshaw used for the testing of PCU.

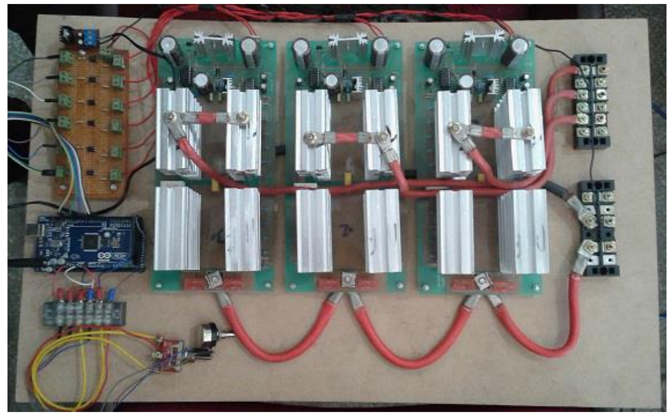

Figure 19: Designed hardware prototype of a PCU

The PCU efficiency is calculated using

$$P = 3\,V\,I\,cos\,(\theta) \qquad (2)$$

where *cos (θ)* is the power factor. While keeping it 0.9, PCU clickes the efficiency of 92.3% at resistive load, which is considered to be efficient using local market componenets and facilities.

Figure 20: Three-wheeler auto rickshaw

V. CONCLUSION

This paper purposes the design and development of a power control unit for a light electric vehicle such as three wheeler auto rickshaw. A PCU proptotype has been designed, simulated in Proteus ISIS, built and finally evaluated. PCU has been verified to function as intended minimizing the manufacturing cost of the PCU as compared to the imported gadget. It was built in lab in approx. 4000 PKR, reducing the price to one fourth successfully. The PCU has been made compact enough to fit in light electric vehicle.

VI. ACKNOWLEDGMENT

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