ISSN (ONLINE): 2395-695X
ISSN (PRINT): 2395-695X

International Journal of Advanced Research in Basic Engineering Sciences and Technology (IJARBEST)
Vol. 2, Issue 10, October 2016

Simulation and Implementation of Electric Bicycle employing BLDC Drive

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Abstract - Electric Bicycles have been gaining attention as an efficient and clean means of transportation. This paper focuses on the design and implementation of a hybrid powered electric bicycle employing a dc-dc power converter. Two DC sources are used: battery and super capacitor. The super capacitor is connected in parallel to the battery and a dc-dc converter is designed in closed loop which arbitrates power between the battery and super capacitor. The purpose of employing super capacitor is to drive the vehicle during the peak power required by the load. The main components of the proposed electric bicycle are: battery, super capacitors, dc-dc converter, controller and BLDC motor. These components are modeled in MATLAB. Three topologies of dc-dc converter are investigated for the electric bicycle and they are compared in terms of ripple at the input and the output and from the results it is found that the modified boost converter results in reduced ripple. The lead acid battery and super capacitor are modeled in SIMULINK to obtain the voltage and current waveform. A prototype of the proposed dc-dc converter is built alongwith controller and it is tested. A real-time working model of electric bicycle is built and the performance of the sources and the power converter are analyzed and the results are verified.

Index Terms- Electric bicycle, ripple, duty cycle, state of charge

I. Introduction

In the present era, there is an increasing demand for transportation and this has led to the vast development in the area of electric vehicles. Bicycle is a mode of transportation which is safe and cheaper and it reduces the air the pollution. Therefore, the use of electric bicycles has increased. Conventionally, dc motors are employed but it suffers from commutation problem and requires frequent maintenance. The deployment of Brushless DC motor (BLDC) for e-cycle overcomes the above problem.The BLDC motor is electrically commutated by power switches instead of brushes and is highly reliable since it does not have any brushes to wear out and replace.

The proposed work employs two power sources in parallel combination which includes the battery and super capacitor[1]. They are given to the main circuit via a switch and microcontroller decides which power source has to be utilized over a particular interval of time. The stator current is measured and when it goes beyond certain load conditions, super capacitor helps battery by charging it. The fact is that the super capacitor is used to supply the motor during the peak load condition where the battery will not be as efficient as possible[2-3]. The block diagram of the proposed work is shown in Fig.1.

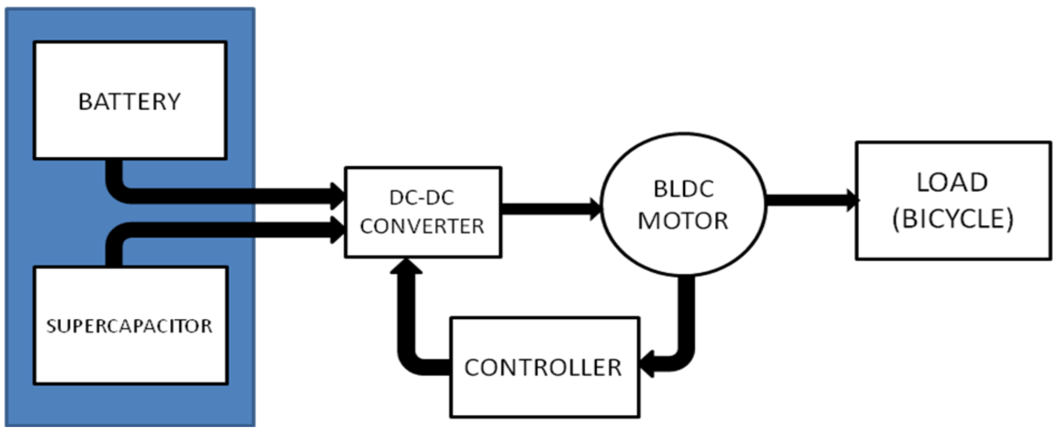

Fig.1. Block Diagram of Electric Bicycle

From Fig.1, when the motor starts rotating, then the wheel of the cycle also starts to rotate. Hence the cycle moves forwards with a constant speed of the motor. The speed can be varied by the use of throttle. When the rider stops accelerating the throttle, the motor stops and hence the cycle also stops.

II.PROPOSED TOPOLOGY OF POWER CONVERTER FOR ELECTRIC BICYCLE

DC-DC power converters are extensively used in all variety of applications, including power supplies for computers, industry equipments, aerospace, telecommunication and motor drives[4-5]. The main function of this converter is to obtain a variable dc from a fixed dc input which can perform buck, boost and buck-boost operation. The most preferred topology is the boost converter in which the output is greater than the input voltage. The three different boost topologies considered in this work are:

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- Boost Converter
- Interleaved Boost Converter
- Modified Boost Converter

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ISSN (PRINT): 2395-695X

International Journal of Advanced Research in Basic Engineering Sciences and Technology (IJARBEST)
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(A) Boost Converter or Step-Up Converter

A boost converter is a switch mode DC to DC converter in which the output voltage is greater than the input voltage and the circuit is shown in Fig.2. It is also called as step up converter. The name step up converter comes from the fact that analogous to step up transformer the input voltage is stepped up to a level greater than the input voltage. By law of conservation of energy the input power has to be equal to output power (assuming no losses in the circuit).

Input power (P_{in}) = output power (P_{out})

Since $V_{in} < V_{out}$ in a boost converter, it follows then that the output current is less than the input current. Therefore in a boost converter

$V_{in} < V_{out}$ and $I_{in} > I_{out}$

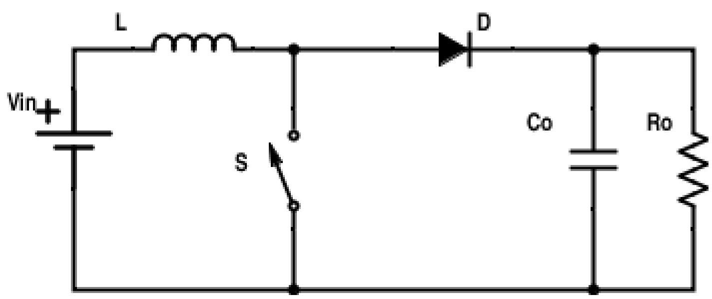

Fig.2. Boost converter circuit

The main working principle of boost converter is that the inductor in the input circuit resists sudden variations in input current. When the main switch is turned on, the inductor current rises to the maximum value and energy is stored in the inductor. When the switch is turned off, the polarity of the emf induced in the inductor reverses as it cannot the change the direction of current instantaneously and hence the freewheeling diode is forward biased. As a result, the inductor discharges and the energy stored in it are transferred to the load and the inductor current decays. Therefore, the voltage across the load will be equal to the sum of the supply voltage and voltage across the inductor. Hence, this converter produces an output greater than the input voltage, thus performing boosting action. The large time constant compared to switching period ensures a constant output voltage.

ISSN (ONLINE): 2395-695X
ISSN (PRINT): 2395-695X

International Journal of Advanced Research in Basic Engineering Sciences and Technology (IJARBEST)
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The conversion gain of boost converter is given by

$$\frac{V_0}{V_{in}} = \frac{1}{1-D} \quad (1)$$

Where V_o is the output voltage, V_{in} is the input voltage and D is the duty ratio of boost converter.

The parameters for simulation of boost converter is shown in Table I.

Table I Simulation parameters of Boost Converter

Parameter	Value
Input voltage(V_{in})	36V
Duty cycle(D)	25%
Switching frequency(f_s)	10KHz
Inductor,L_1	12.5mH
Capacitor	20μF
Resistor	100Ω

The simulation circuit of boost converter is shown in Fig.3.

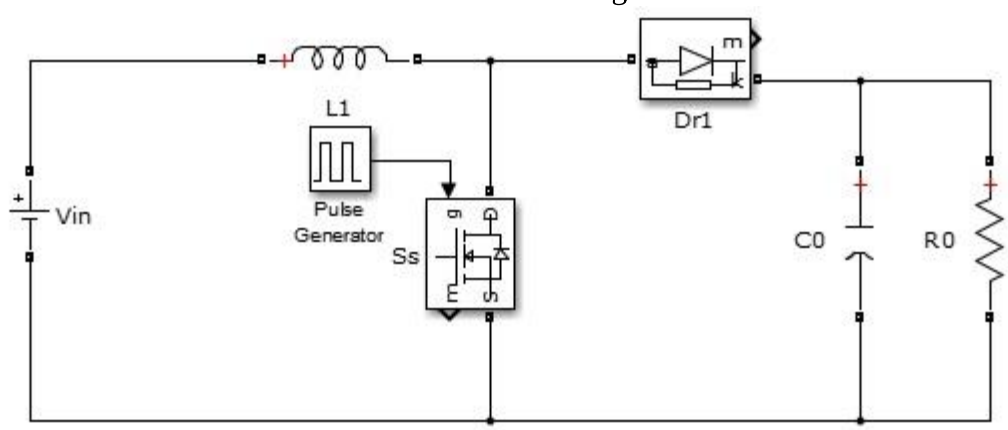

Fig.3. Simulation circuit of boost converter

ISSN (ONLINE): 2395-695X
ISSN (PRINT): 2395-695X

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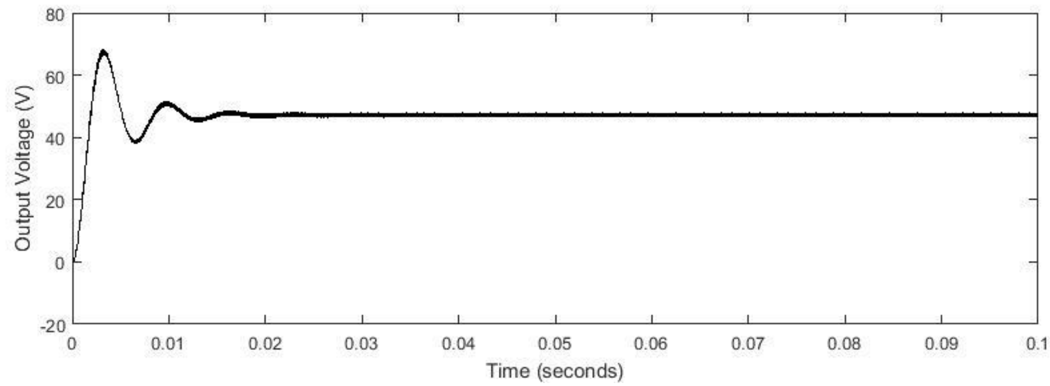

Fig. 4. Output voltage waveform

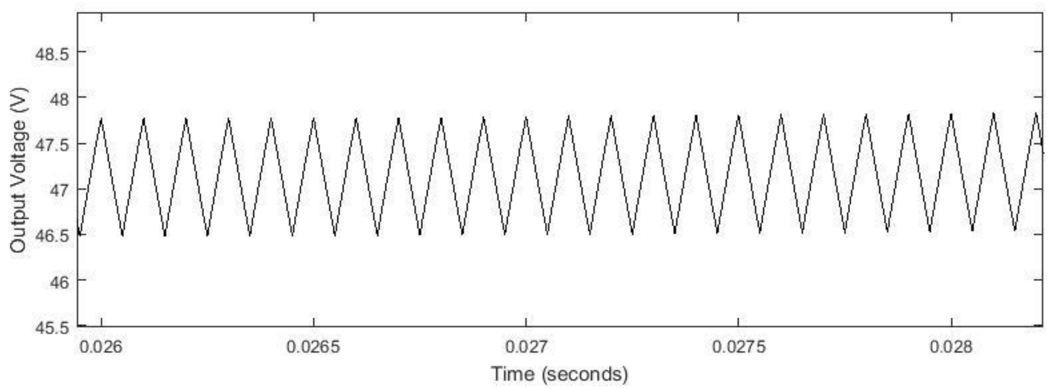

Fig.5. Output voltage ripple waveform

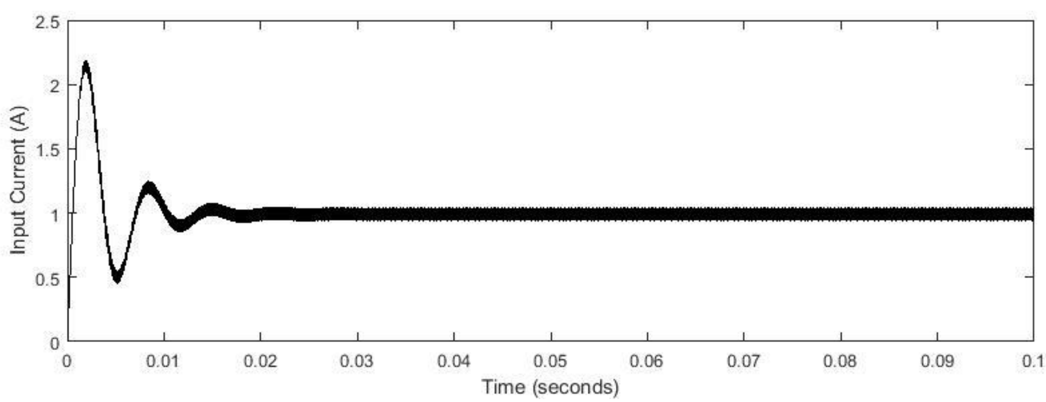

Fig.6. Input current waveform

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ISSN (PRINT): 2395-695X

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Figures 4-7 represent the output voltage waveform, output voltage ripple, input current and input current ripple for a boost converter.

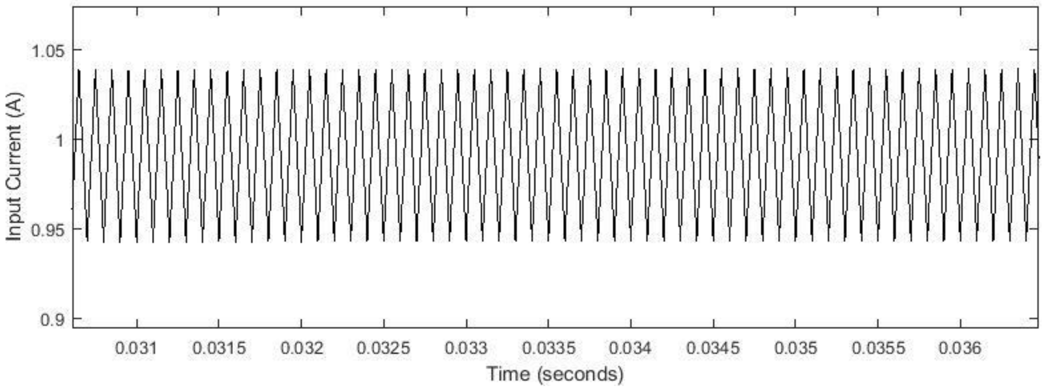

Fig.7. Input current ripple waveform

Thus, a boost converter circuit is given an input voltage of 36V, and a switching frequency of 10KHz and is simulated using Matlab/Simulink software and the output voltage waveform is obtained. It is found that an output voltage of 48V is obtained for a duty cycle of 25%.

(B) Interleaved Boost Converter

Boost Converter is a popular topology for most of the power electronic systems by serving as a pre-regulator due to its simplicity in design and high performance. However, as the power rating increases, it is necessary to connect converters in series or parallel. In high power rating applications, interleaving of boost converters is usually employed to improve the converter performance and also to partially reduce the input current, output voltage and inductor current ripple and step down the converter size effectively[6]. As interleaving doubles the switching frequency and effectively reduce the ripple at the input current and output voltage, the size of energy storage elements also significantly reduces. Additionally, it improves the transient response and increases the voltage gain of the converter. The circuit diagram of a two-phase IBC is shown in Fig.8.

ISSN (ONLINE): 2395-695X
ISSN (PRINT): 2395-695X

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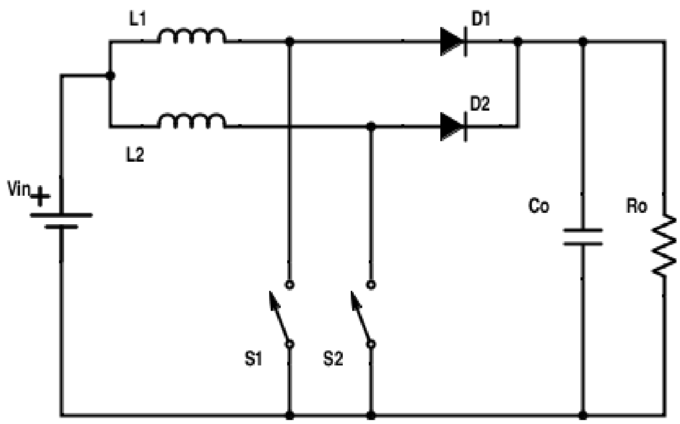

Fig.8. Circuit Diagram of Interleaved boost converter

In general, the frequency and phase shift are same for each parallel connected unit in the IBC. Operation of two-phase IBC is explained as follows: when Q_1 is turned on the current in the inductor iL_1 increases linearly and at the same time energy is stored in inductor L_1. When Q_1 is turned off, diode D_1 conducts and the stored energy in the inductor decreases with a slope of the difference in the input and output voltage. When the inductor discharges its energy, the transfer the current to the load takes place via the diode. Once half switching cycle of Q1 is completed, Q_2 is also turned on and completes same cycle of actions. The current ripple produced will be very small as there is a cancellation of ripples due to phase shift of 180˚ in the switching pulses.

The design of magnetic elements in this circuit plays an important role for storing energy and filtering. The two-phase IBC requires two identical inductors for achieving balanced current. The value of the inductor can be calculated as per the following equation.

$$L = \frac{V_{in}\, M}{f_s\, \Delta I_L} \tag{3}$$

Where, M – duty ratio, V_{in} – Input Voltage, f_s-Switching frequency and ΔI_L – Inductor current ripple.

The value of the capacitor can be calculated by the following equation.

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$$C = \frac{I_0 M}{f_s \Delta V_C} \quad (4)$$

Where, M – duty cycle, f_s-Switching frequency, ΔV_C – Change in output voltage, I_o –Output current.
The parameters for simulation of IBC are shown in Table II.

Table II Simulation parameters of IBC

Parameter	Value
Input voltage(V_{in})	36V
Duty cycle(D)	25%
Switching frequency(f_s)	10KHz
Inductors(L_1 and L_2)	12.5mH
Capacitor	20µF
Resistor	100Ω

The simulation circuit of two-phase IBC is shown in Fig.9.

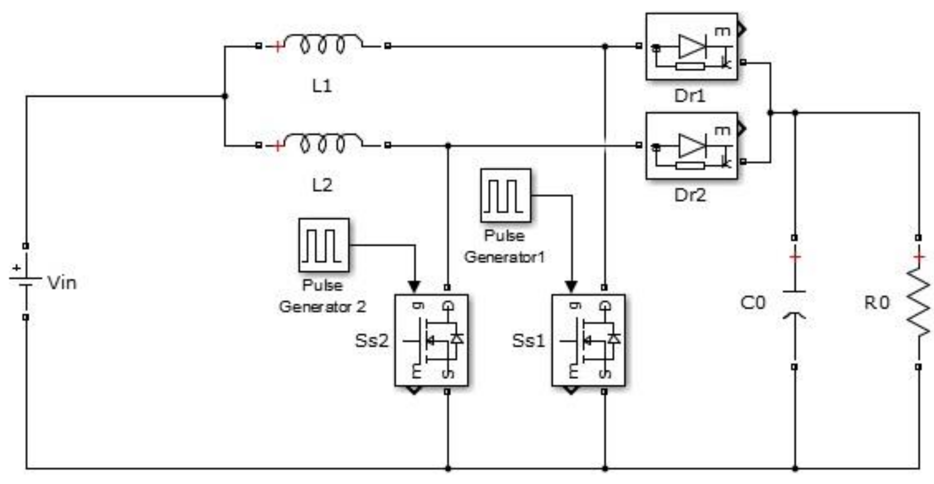

Fig.9. Simulation circuit of interleaved boost converter

Figures 10-13 represent the output voltage waveform, output voltage ripple, input current and input current ripple for an interleaved boost converter.

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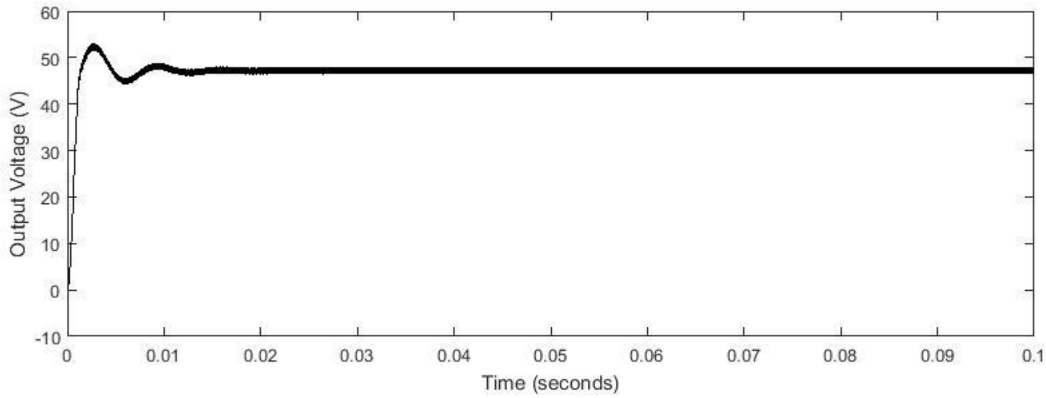

Fig.10. Output voltage waveform

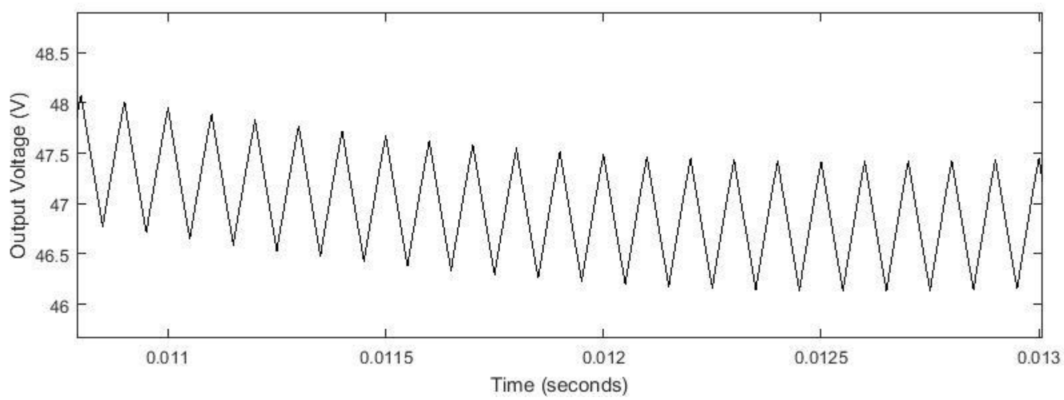

Fig.11. Output voltage ripple waveform

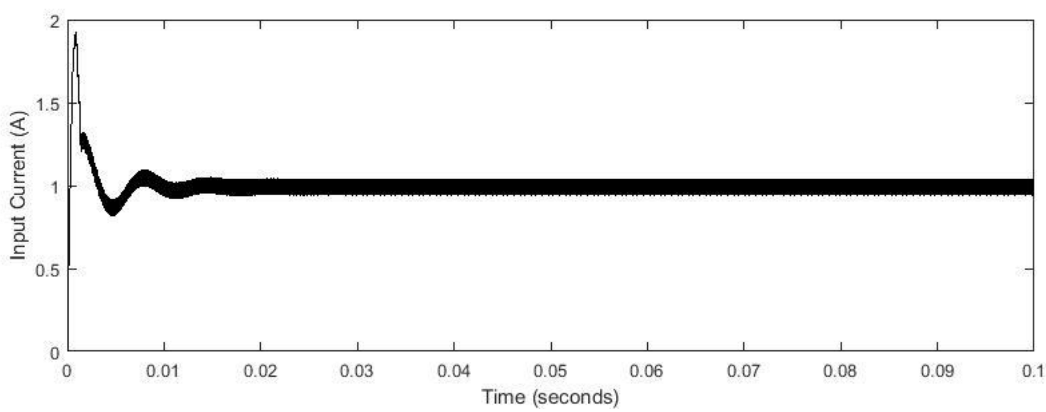

Fig.12. Input current waveform

ISSN (ONLINE): 2395-695X
ISSN (PRINT): 2395-695X

International Journal of Advanced Research in Basic Engineering Sciences and Technology (IJARBEST)
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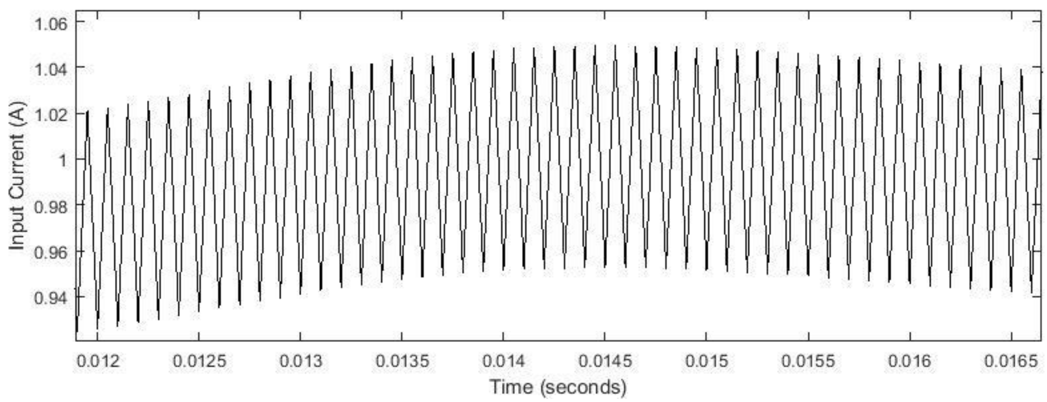

Fig.13. Input current ripple waveform

Thus, an interleaved boost converter circuit is given an input voltage of 36V, and a switching frequency of 10KHz and is simulated using Matlab/Simulink software and the output voltage waveform is obtained. It is found that an output voltage of 48V is obtained for a duty cycle of 25%.

(C) Modified Boost Converter

The circuit diagram shown in Fig.14 represents the two energy storage systems: the super capacitor and the battery. According to the load level, the power semiconductor S_1 is on during the time t_{ON}. The main challenge of the work is to use in the same circuit super capacitors and batteries and to manage the energy in each one, without changing the DC-DC power converter topology. To get this objective, the Fig.14 circuit was implemented together with a specific control strategy. The control strategy should, first of all, control the states of the switches S_2 and S_3 in order to prolong the autonomy of the electrical vehicle and improve the efficiency of the circuit. On the other hand, it should avoid simultaneous operation of the battery and the super capacitors. In this case, a fast discharge of both energy storage systems would be observed.

ISSN (ONLINE): 2395-695X
ISSN (PRINT): 2395-695X

International Journal of Advanced Research in Basic Engineering Sciences and Technology (IJARBEST)
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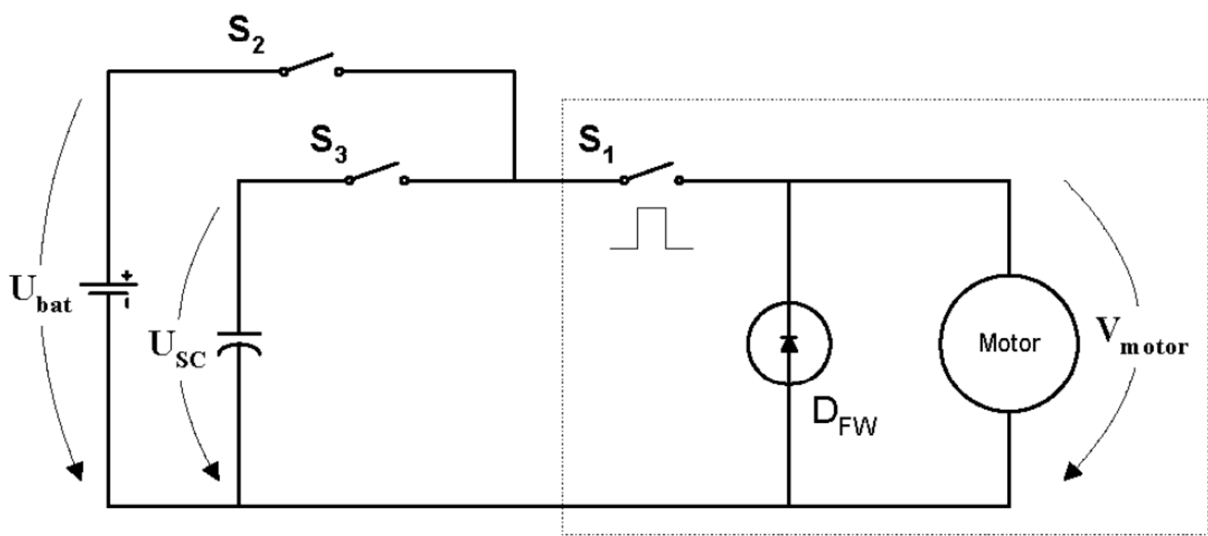

Fig.14. Circuit Diagram of Modified Boost Converter

The main blocks of the proposed system are the motor, the DC-DC converter, the battery, the super capacitors, the controller and the decision circuit. About the decision circuit, distinct conceptions and strategies are possible and acceptable. Here, the super capacitors supply the system when high current peaks are demanded. So, a current level was defined ($I_{a\text{-}sc}$) imposing the super capacitors supplying the system (when: $I_{load} > I_{a\text{-}SC}$) or the batteries (when: $I_{load} < I_{a\text{-}SC}$).

The parameters for simulation of MBC are shown in Table .III

Table III Simulation parameters of MBC

Parameter	Value
Input voltage(V_{in})	36V
Duty cycle(D)	25%
Switching frequency(f_s)	10KHz
Capacitor	20µF
Resistor	100Ω

The simulation circuit of modified boost converter is shown in Fig.15.Figs 16-17 represents the output voltage and ripple waveform of MBC.

ISSN (ONLINE): 2395-695X
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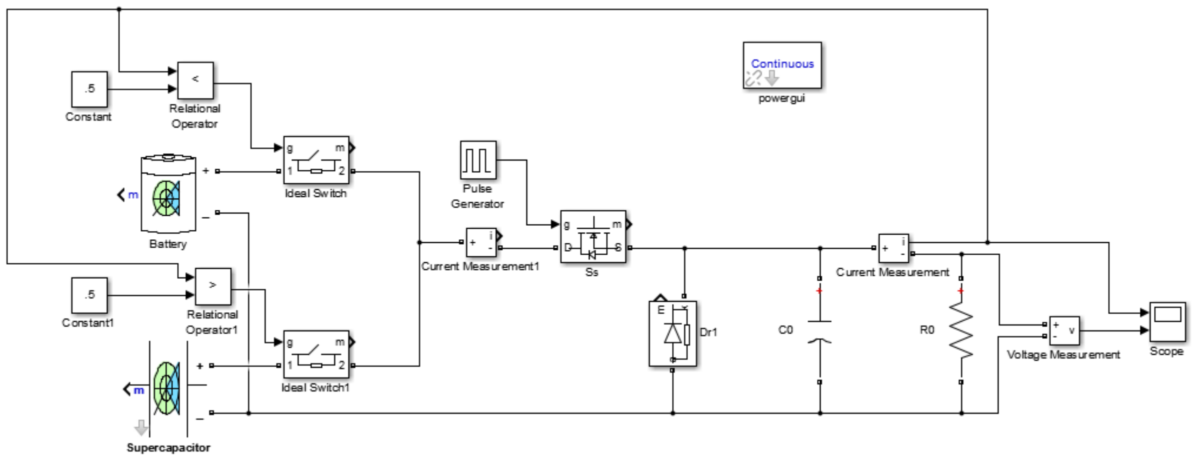

Fig.15. Simulink Circuit of MBC

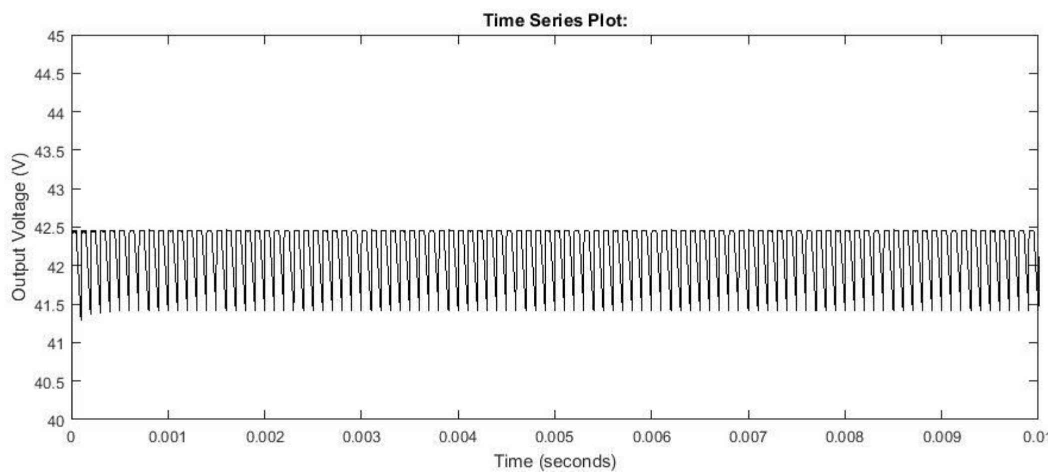

Fig.16 Output voltage waveform

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ISSN (PRINT): 2395-695X

International Journal of Advanced Research in Basic Engineering Sciences and Technology (IJARBEST)
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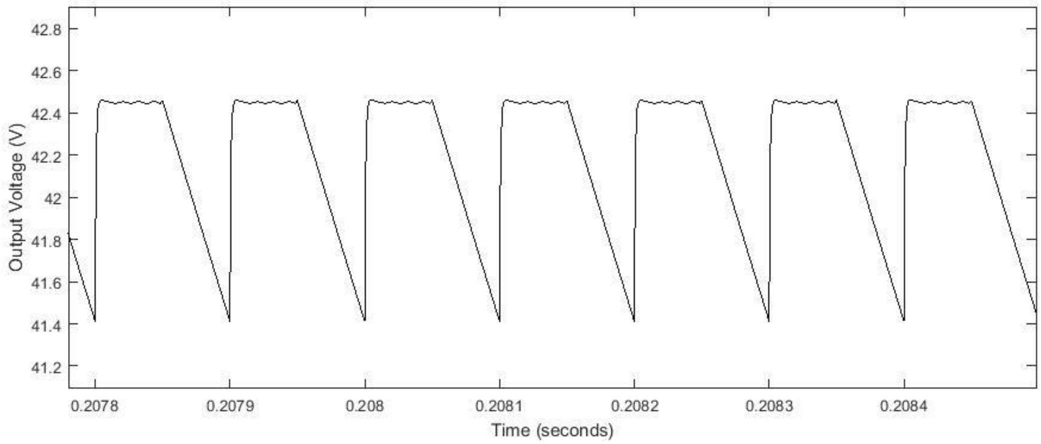

Fig.17 Output voltage ripple waveform

Thus, a modified boost converter circuit is given an input voltage of 36V, and a switching frequency of 10kHz and is simulated using Matlab/Simulink software and the output voltage waveform is obtained. It is found that an output voltage of 42V is obtained for a duty cycle of 25%.

The comparison between the three topologies of the converter are carried out on the basis of (i) Output Voltage Ripple and (ii) Input Current Ripple and Fig.18 & 19 shows the output voltage ripple and input current ripple values of the different converter topologies .

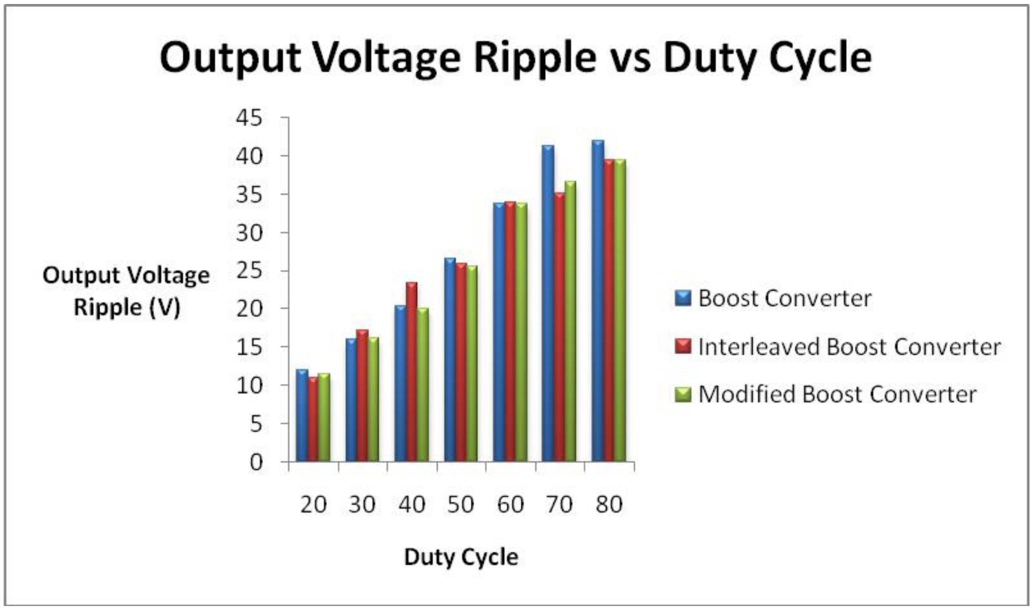

Fig.18. Output Voltage Ripple vs Duty Cycle

Fig.18 shows that the MBC has the lowest ripple compared to the other two topologies and hence this topology is selected for developing the prototype for e-cycle.

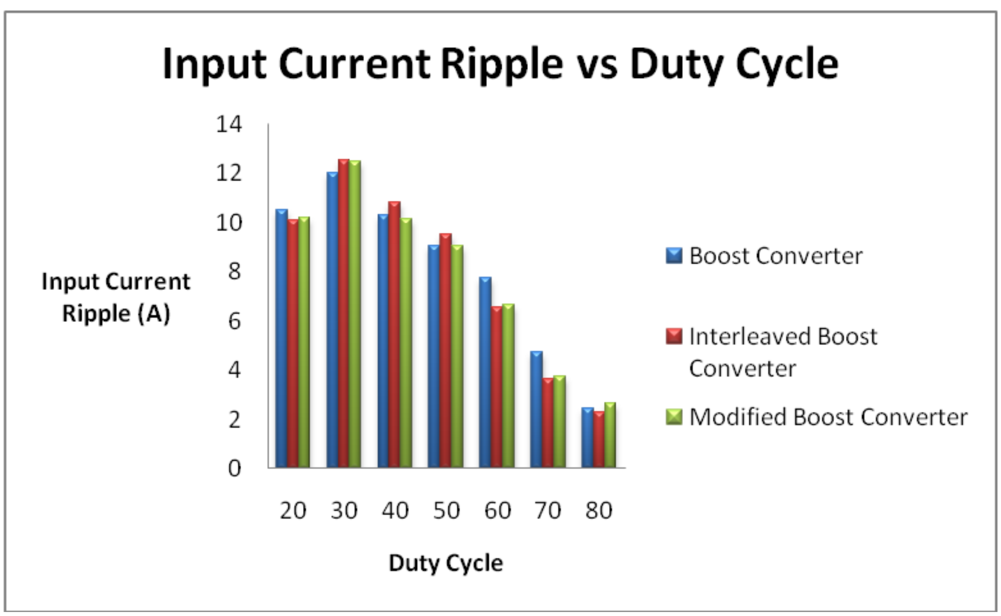

Fig.19. Input Current Ripple vs Duty Cycle

ISSN (ONLINE): 2395-695X
ISSN (PRINT): 2395-695X

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On comparing all the topologies, it has been found that the best topology that suits for the work is modified boost converter. On comparing with other two topologies, MBC has less ripple voltage and ripple current at the output and input side respectively. Also the efficiency is high in MBC when compared to other two topologies.

III.SIMULATION OF BLDC DRIVE

The Brushless DC (BLDC) motor is the ideal choice for applications that require high reliability, high efficiency, and high power-to-volume ratio. Generally speaking, a BLDC motor is considered to be a high performance motor that is capable of providing large amounts of torque over a vast speed range[7-8]. For the proposed electric cycle, BLDC hub motor is chosen and the simulink model is shown in Fig.20.

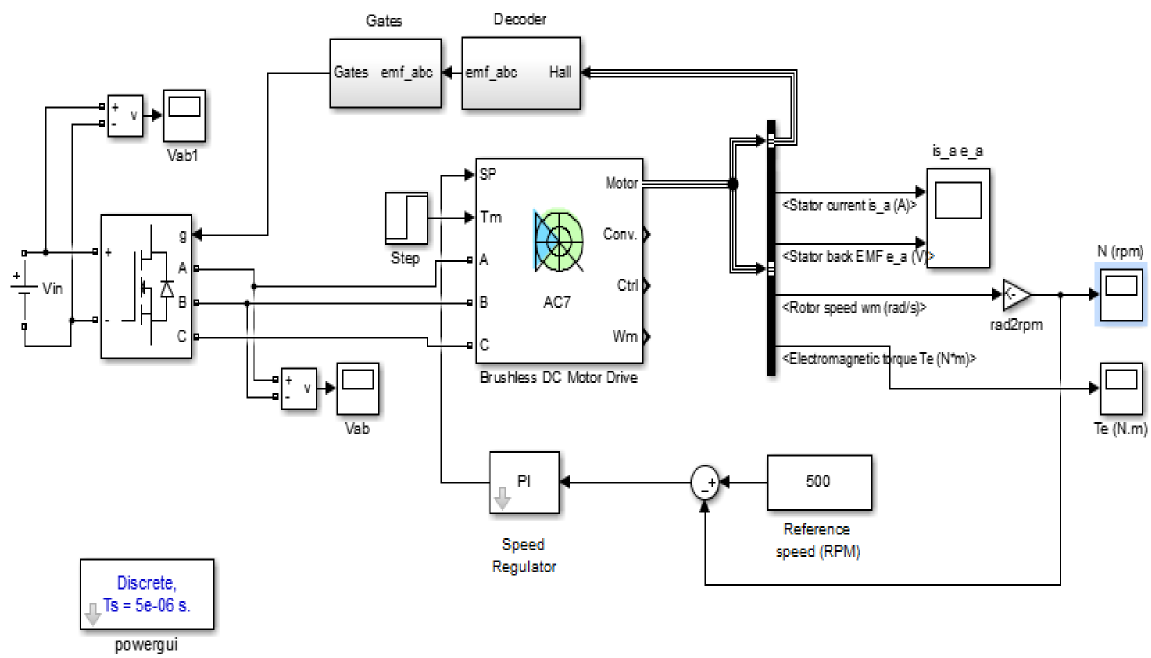

Fig.20. Simulation circuit of BLDC drive

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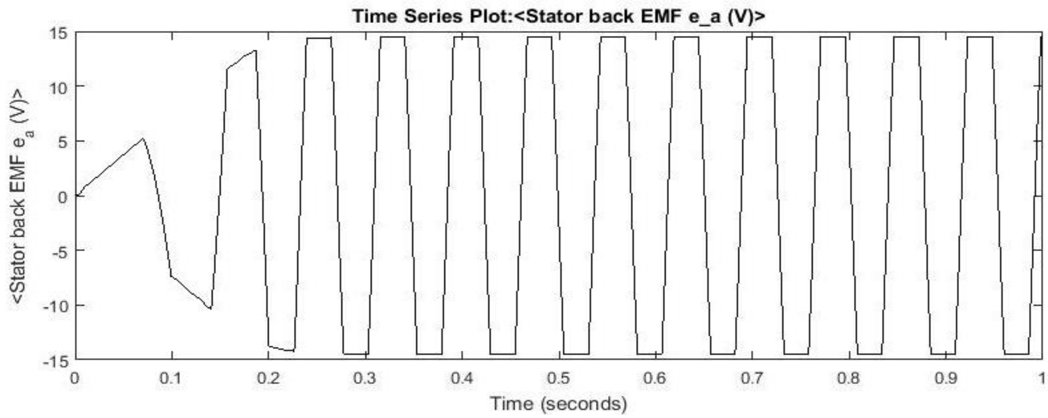

Fig.21 Stator Back EMF Waveform

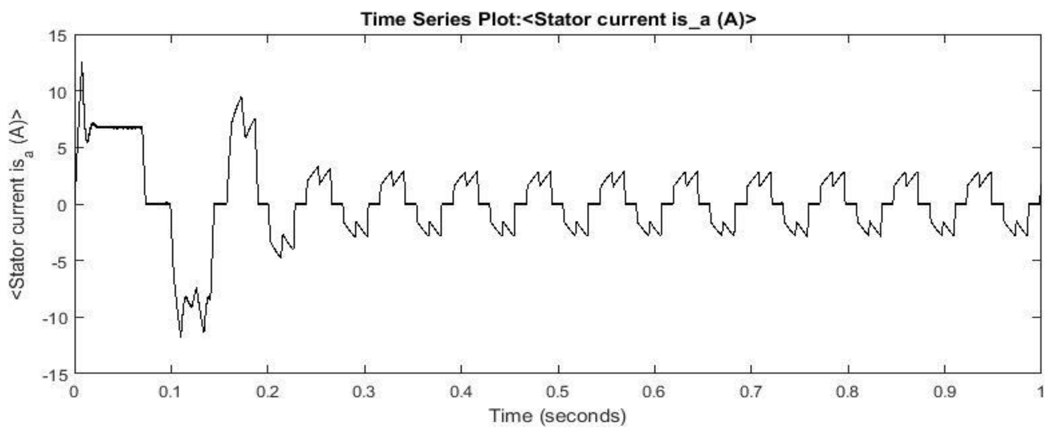

Fig.22 Stator Current Waveform

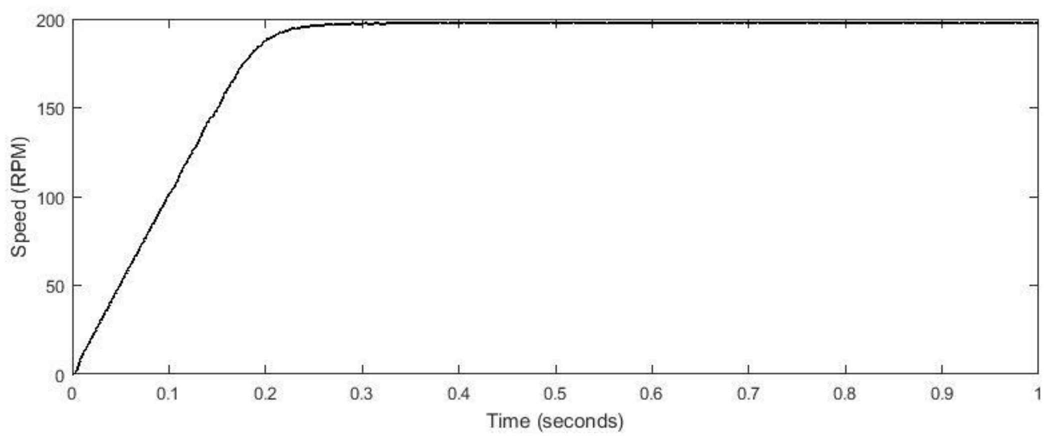

Fig.23 Rotor Speed Waveform

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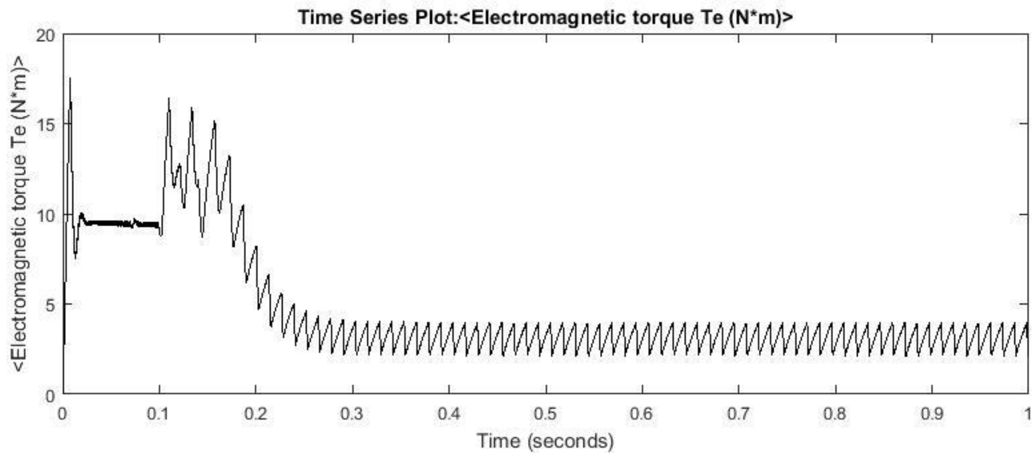

Fig.24 Electromagnetic Torque Waveform

Thus, a model of the BLDC motor is simulated using Matlab/Simulink, with an input of 36V and the corresponding output speed, torque, stator current and back emf waveforms are obtained as shown in Figs.21-24 . The simulink model of the entire circuit is shown in Fig.25.

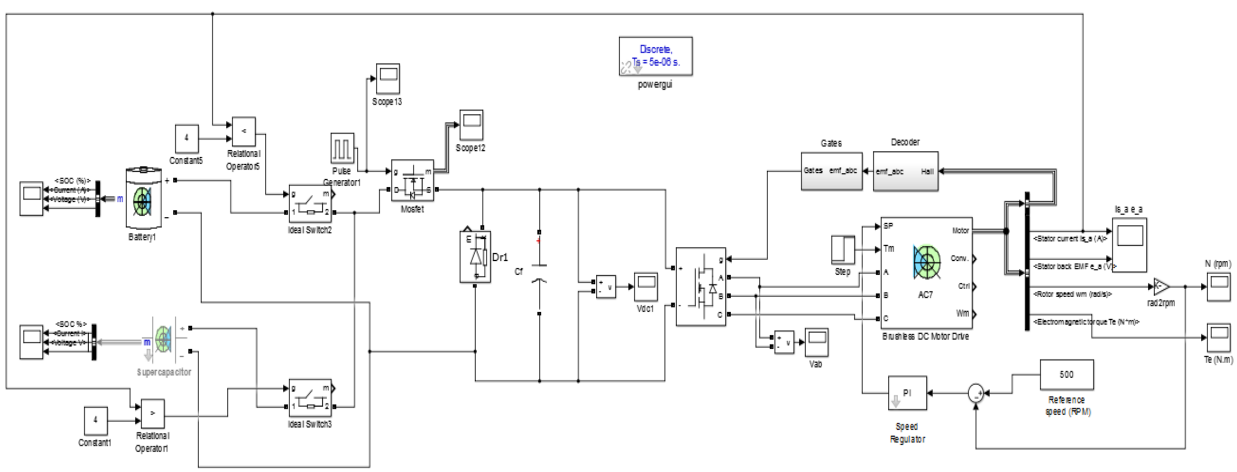

Fig.25 Simulation Circuit of Bicycle

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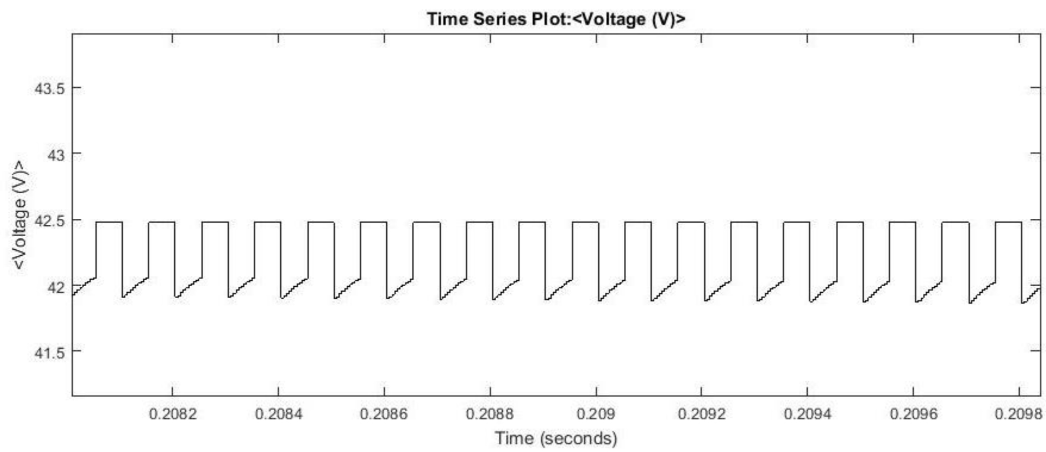

Fig.26. Voltage Waveform of Battery

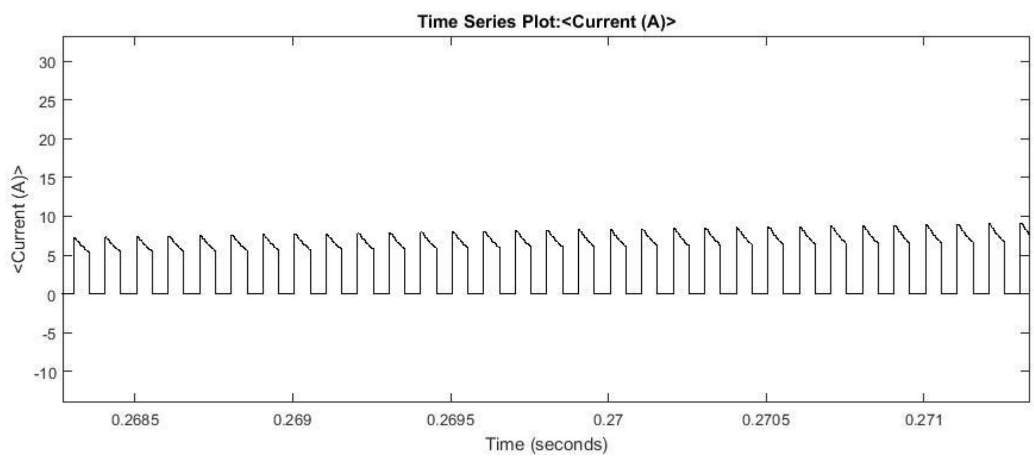

Fig.27. Current Waveform of Battery

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ISSN (PRINT): 2395-695X

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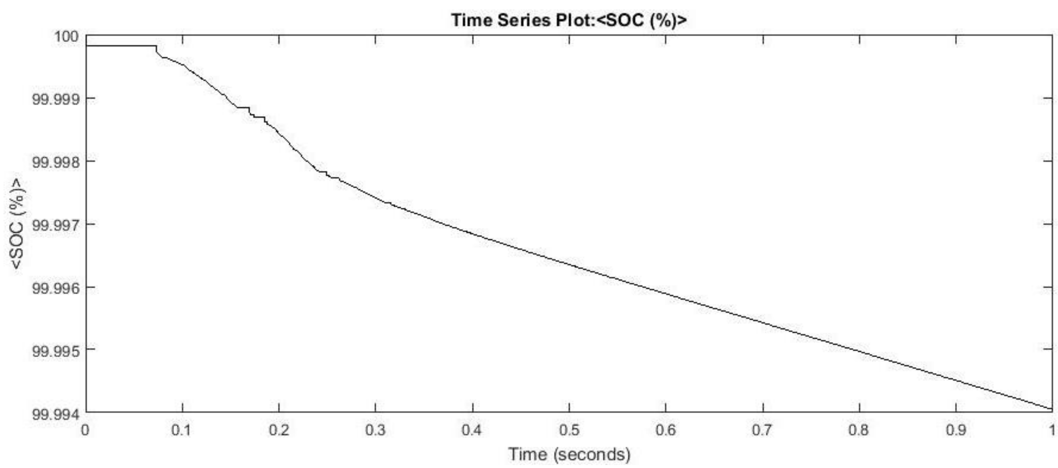

Fig.28. SOC Characteristics of Battery

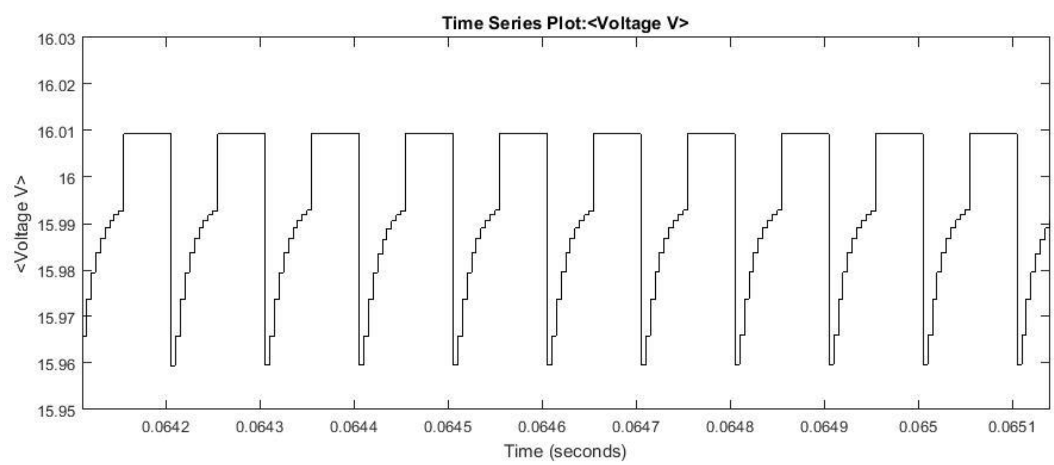

Fig.29. Voltage Waveform of Supercapacitor

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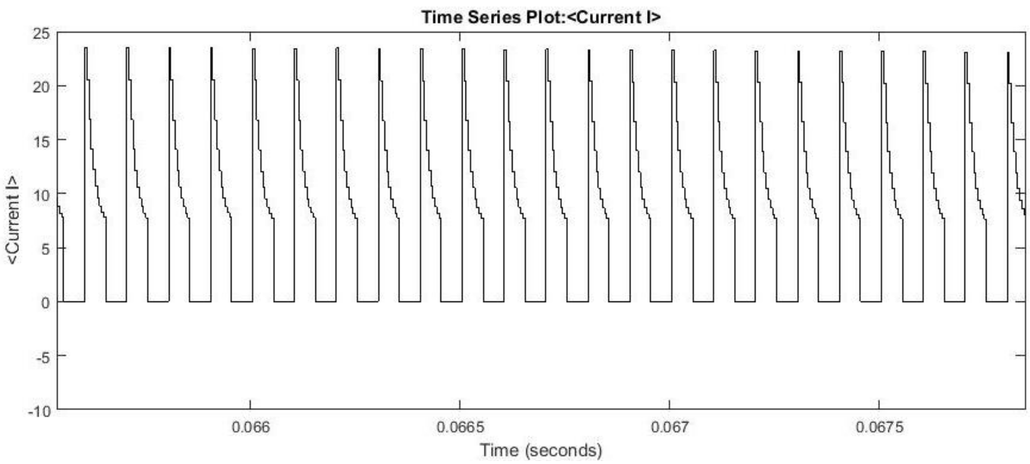

Fig.30. Current Waveform of Super capacitor

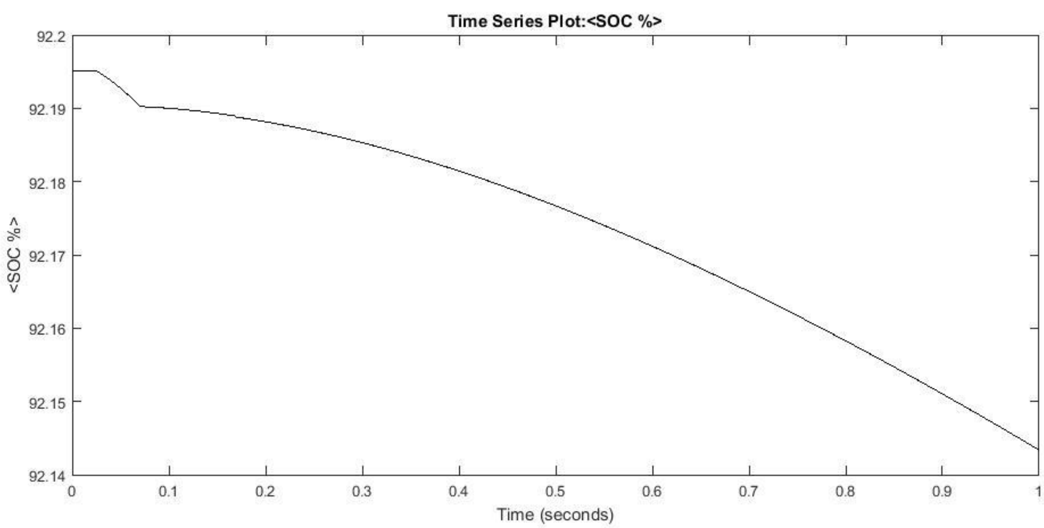

Fig.31. SOC Characteristics of Super capacitor

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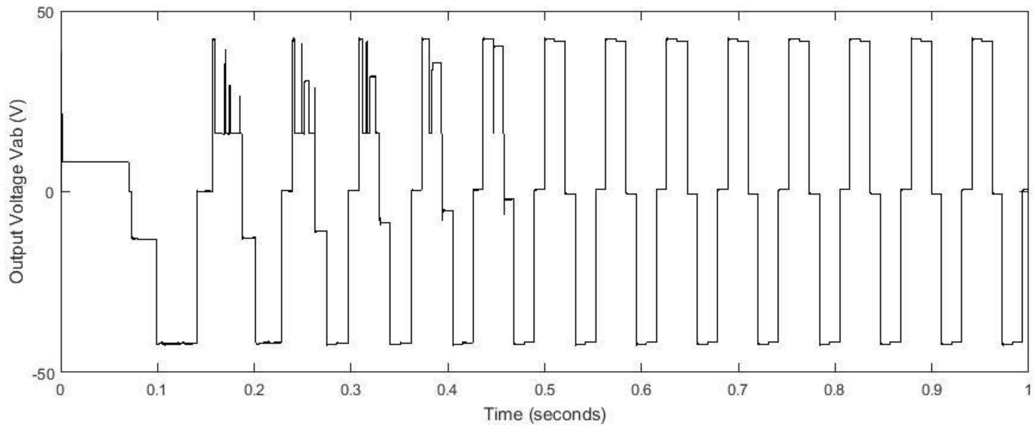

Fig.32 Output Voltage of Inverter (V_{ab})

From Fig.25, it is clear that the electric bicycle is powered from two sources namely battery and super capacitor. The battery voltage, current and SOC waveforms are shown in Figs. 26-28.The super capacitor voltage, current and SOC waveforms are shown in Figs.29-31. Fig.32 gives the output voltage of the voltage source inverter.

IV. Hardware Implementation

The hardware for the design and implementation of electric bicycle consists of an INDUINO R3 to generate gate pulses to the switch, a converter circuit and a BLDC motor. The gating circuit includes the Induino, and the optocoupler arrangement. The supply voltage for the optocoupler IC is provided from lead acid battery. The supply voltage is 12 V. The gating circuit is as shown in Fig.33.

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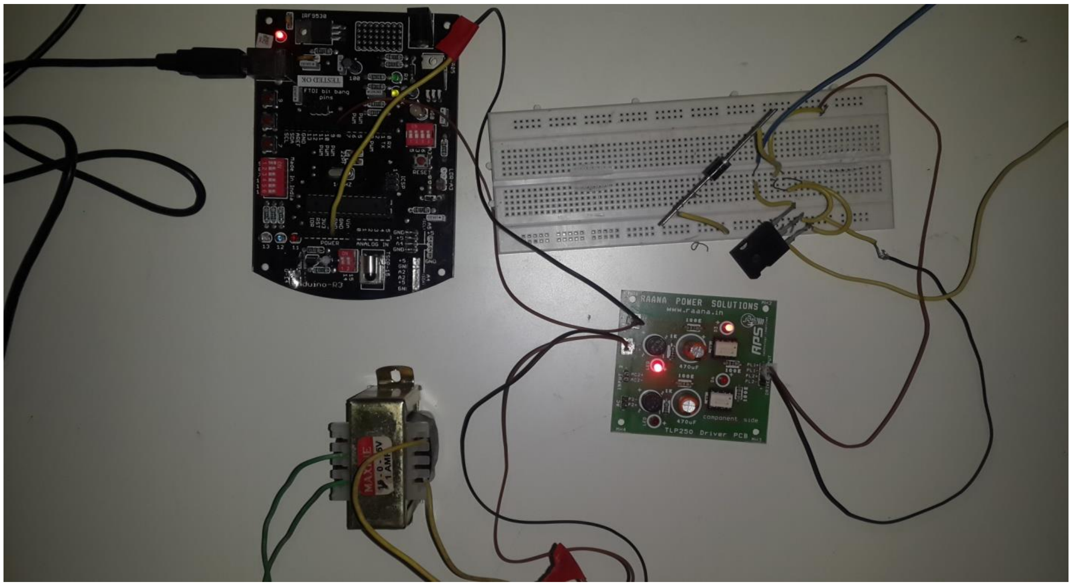

Fig.33. Gating circuit

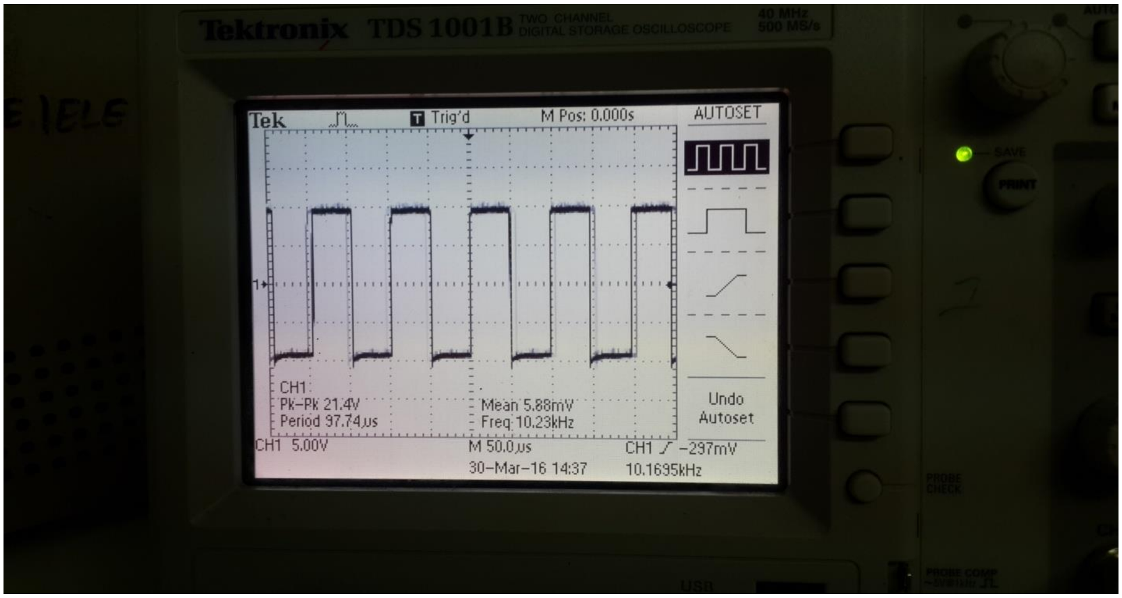

Fig.34. Gating pulse waveform

The converter circuit consists of power mosfet, fast recovery diode, output filter capacitor and output load as shown in Fig.35. The input to the converter is given from a series of three

ISSN (ONLINE): 2395-695X
ISSN (PRINT): 2395-695X

International Journal of Advanced Research in Basic Engineering Sciences and Technology (IJARBEST)
Vol. 2, Issue 10, October 2016

batteries. The output of the converter is given to the BLDC Motor controller. The complete circuit with is shown in Fig.36.

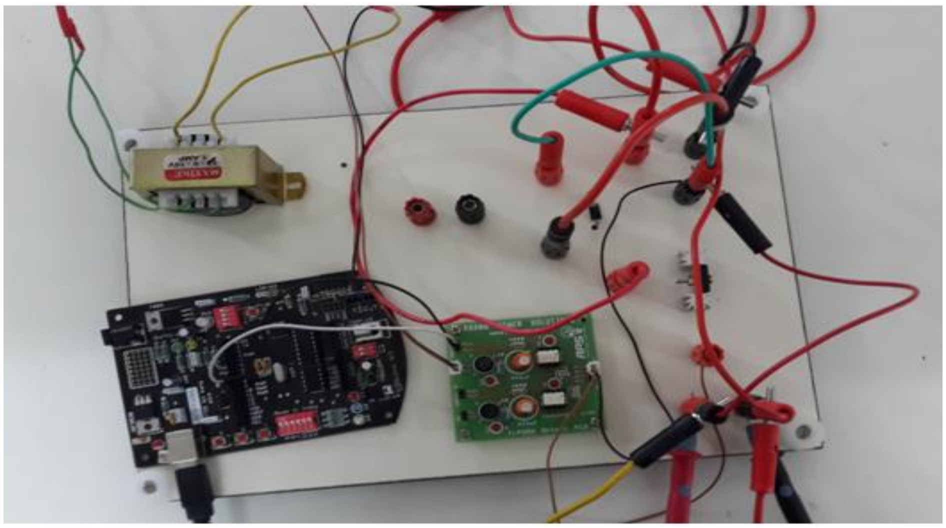

Fig.35. Converter circuit

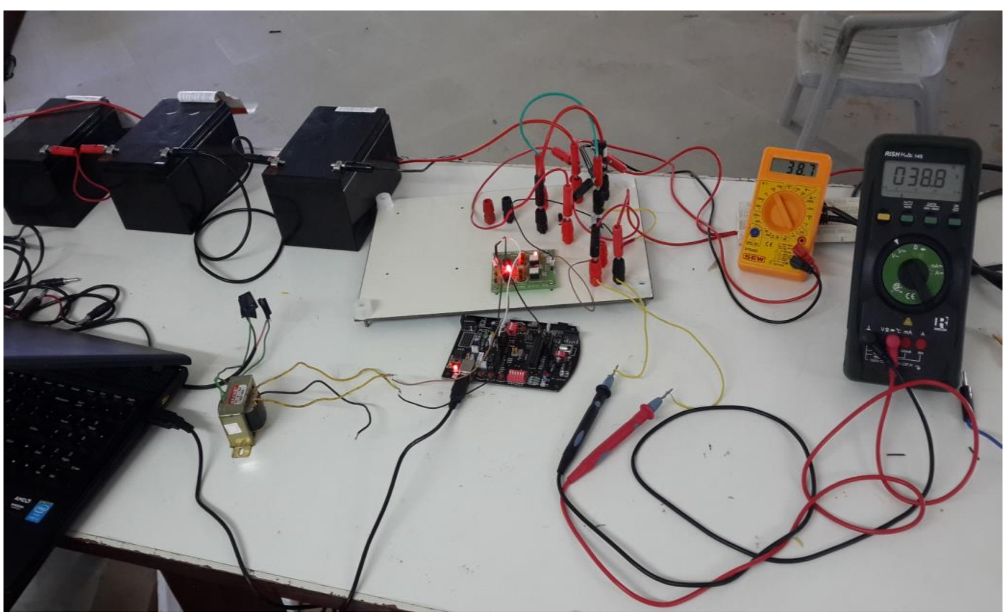

Fig.36. Complete circuit

The hardware implementation of the proposed work is executed and the output voltage of 36V is obtained. The prototype of the electric cycle is shown in Fig.37. fitted with BLDC drive and the proposed boost converter.

Fig.37. Prototype of Electric Cycle

V.CONCLUSION

The proposed work provides a hybrid storage system which increases the run time of bicycle, making the system economic and efficient. Various converter topologies like the interleaved boost converter boost converter, modified boost converter are analyzed and a comparison of these topologies is made by calculating the ripple content of the output voltages .Modified boost converter with its simple circuit, less switching losses, low ripple content is chosen for the hardware implementation. For an input voltage of 36V, the bicycle runs at the speed of 25km/hr. Thus by using this hybrid powered electric bicycle we can have pollution less environment.

ACKNOWLEDGMENT

The project work was funded by the SSN Institutions under Student's funding scheme and the authors wish to thank the SSN Institutions for providing the financial support and computational facility in carrying out the research work.

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