CIRCUIT DESIGN AND SIMULATION OF LOW VOLTAGE ENERGY HARVESTING USING SWITCHING CONVERTERS

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Abstract

This paper presents the simulation of low voltage energy harvesting using an ac/dc step up converter with the power electronic simulation software PSIM©. The direct ac/dc conversion is achieved with boost and buck boost converters connected in parallel which are operated in positive and negative half cycles respectively. The input supply is from micro generators which scavenge energy from ambient which is of the order of milli volts. The output is to be supplied to an electronic load which has an input supply voltage of 3.3 V. The design of the converter and the simulation with a closed loop control is being realized.

Index Terms Boost Converter, Buck boost converter, Micro generators.

I. INTRODUCTION

In the present scenario of global warming, self powered devices play a very important role. They can perform their operations without any external supply by scavenging energy from the environment. With the ever reducing power requirements of both analog and digital circuits, power scavenging approaches are becoming increasingly attractive. Fabrication of such power sources using MEMS (Micro Electro Mechanical Systems) technology is attractive in order to achieve small size and high precision.

The power requirements of electronic devices has been considerably reduced because of the developments of the high efficient semiconductor devices. This leads to the development of the electronic devices such as wireless sensors, medical implants etc. Usually batteries have been traditionally used as the energy source for such low power wireless applications. However, they are limited by their capacity and size. Moreover, they need to be recharged and replaced periodically. The power requirement of these electronic devices are of the order of a few milli watts which can be harvested from the ambient energy in the form of heat, light, vibration etc by using various types of micro generators. The types of micro generators include electromagnetic, electrostatic, piezoelectric [3]-[5]. Since micro electromagnetic generators have the high energy density, they are being considered in this work.

The ambient mechanical vibration is converted into electrical energy in order to power low power electronic devices through a variable capacitor is being designed using MEMS technology [6]. Using MEMS technology, a system incorporating electrostatic motion driven generator for low frequency motion is developed [4]. Buck boost converter is incorporated for low voltage energy harvesting using vibration based piezoelectric generators are designed with MEMS technology [5].

A micro electromagnetic generator consists of a permanent magnet, copper coils and a spring as shown in Fig. 1. The base is attached to permanent magnet through a spring. The permanent magnet is kept in between the coils. Whenever the base is vibrated, the magnetic flux produced by the permanent magnet is cut by the coil thereby there is a rate of change of flux linkages. So a sinusoidal electromagnetic force is generated according to Faraday's laws of electromagnetic induction. Since the ac voltage generated by the micro electromagnetic generator is very small which is of the order of a few hundred milli

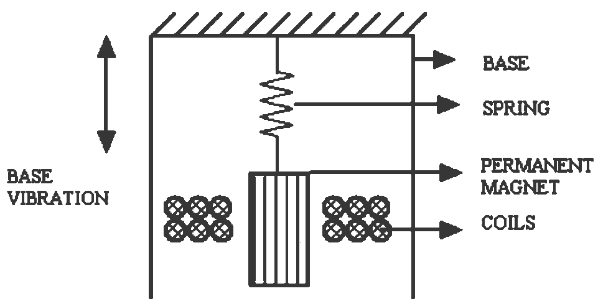

Fig. 1. Micro electromagnetic generator

volts, it needs a power electronic interface circuit to convert this low voltage into the minimum voltage required by an electronic circuit and to convert it into a DC supply and also to store the electric power in the power storage elements.

The block diagram for low voltage energy harvesting is shown in Fig. 2. The ambient vibration is converted into electrical energy by the MEMS transducer. The output of the transducer is an ac voltage with a low magnitude which has to be converted into a dc voltage and also to be stepped up to the required value to supply the low power electronics load.

Since the voltage generated by the micro electromagnetic generator is an ac voltage which is of the order of few milli volts and the load is an electronic device which needs a dc supply of the order of a few volts, there are two stages involved in this conversion process. They are rectification and boosting processes [4]. So the conventional power converters reported for energy harvesting circuits consist of a diode bridge rectifier and a dc/dc converter for stepping up the voltage as shown in Fig. 3.

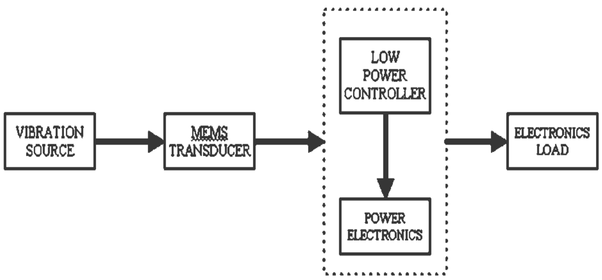

Fig. 2. Block diagram for low voltage energy harvesting.

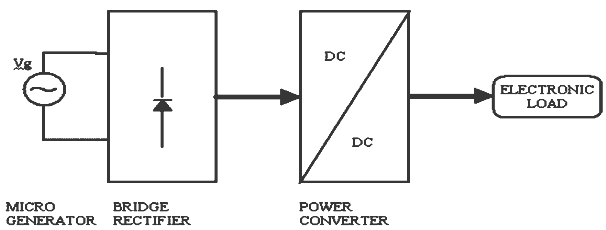

Fig. 3. Conventional power converter

The main disadvantage in this two stage topology is since the output of micro generators are very low, the rectification is not possible with the conventional diodes. If possible also, the forward voltage drop in the diodes causes losses as input current is much higher than output current thereby the power conversion efficiency is decreased [1].

This leads to the development of direct AC/DC step up converter which converts the ac voltage with low magnitude generated by the micro electromagnetic generator into a dc voltage with a higher magnitude thereby avoiding diode bridge rectifier. The block diagram for low voltage energy harvesting with an ac/dc step up converter is shown in Fig. 4.

The proposed ac/dc step up converter consists of a boost converter which operates during the positive half cycle of the input voltage and a buck boost converter which operates during the negative half cycle of the input voltage as shown in Fig. 9. Both the converters are operated in the DCM (Discontinuous Conduction Mode) since the input current of buck boost converter is discontinuous under default circuit operation. The advantages of operating the converters in DCM are (a) it helps in easy implementation of control scheme and (b) it reduces switching losses of converter.

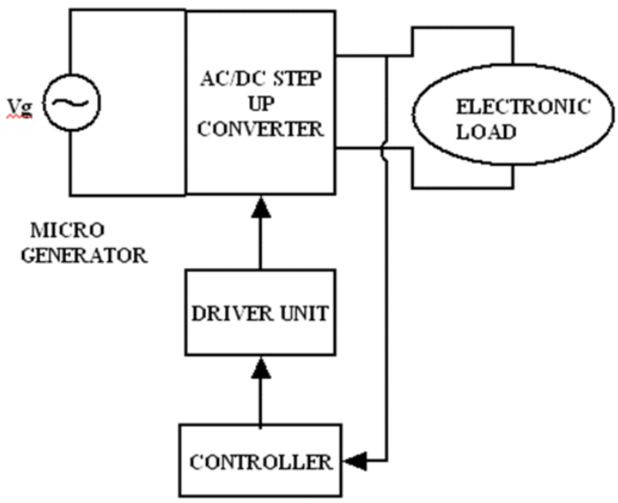

Fig. 4. Block diagram for low voltage energy harvesting with an ac/dc step up converter.

II. BOOST CONVERTER

A boost converter is a well known switched mode converter that is capable of producing a dc voltage greater in magnitude than the dc output voltage. A practical realisation of the converter using the switch (MOSFET), diode, inductor and capacitor is shown in Fig. 5.

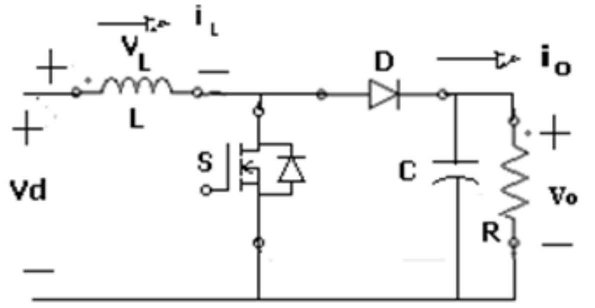

Fig. 5. Basic Boost converter

The operation of the circuit is divided into two modes as shown in Fig. 6 (a). When the switch is on, the inductor stores energy and the capacitor discharges through the load. When the switch is off, the energy stored in the inductor is transferred to the load and is also used to charge the capacitor.

Analysing the circuit for two cases (switch open and switch closed) as shown in Fig. 6 (a) by applying Kirchhoff's rules around the loops and rearranging the terms for the discontinuous conduction mode results in the following relation [8]:

$$\frac{V_o}{V_d} = \frac{\Delta 1 + D}{\Delta 1} \qquad ...(1)$$

The discontinuous conduction mode occurs due to decreased output load power. So I_L decreases hence a discontinuous I_L since V_d is constant as shown in Fig. 6 (b).

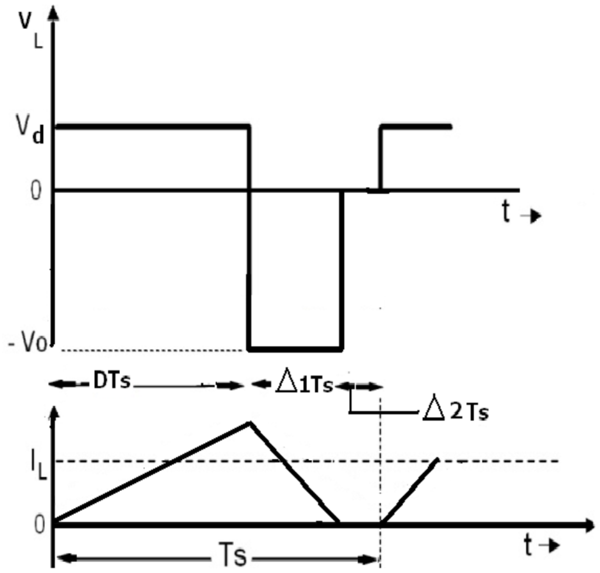

Fig. 6 (b) [8]. Discontinuous conduction mode-waveforms of a boost converter

In discontinuous operation, the output voltage not only depends on the duty cycle, but also on inductor current value, the input voltage, and the output current.

III. BUCK BOOST CONVERTER

A buck boost converter shown in Fig. 7 provides an output voltage that is less than or greater than the input voltage. The output voltage polarity is opposite to that of the input voltage. The input current is discontinuous.

The operation of the circuit is divided into two modes as shown in Fig. 8 (a). When the switch is on, the inductor stores energy and the capacitor discharges through the load. When the switch is off, the energy

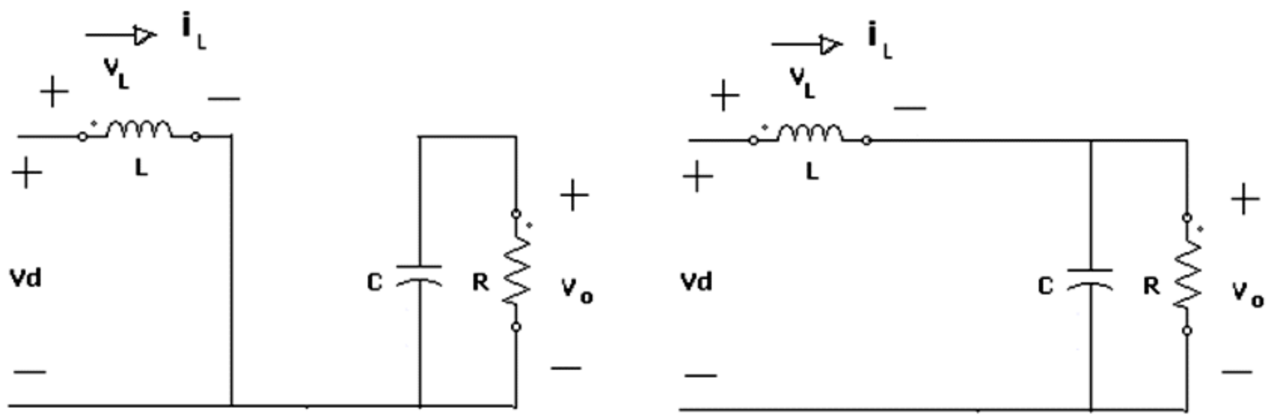

Fig. 6 (a) [8]. Boost converter in switch on and switch off modes

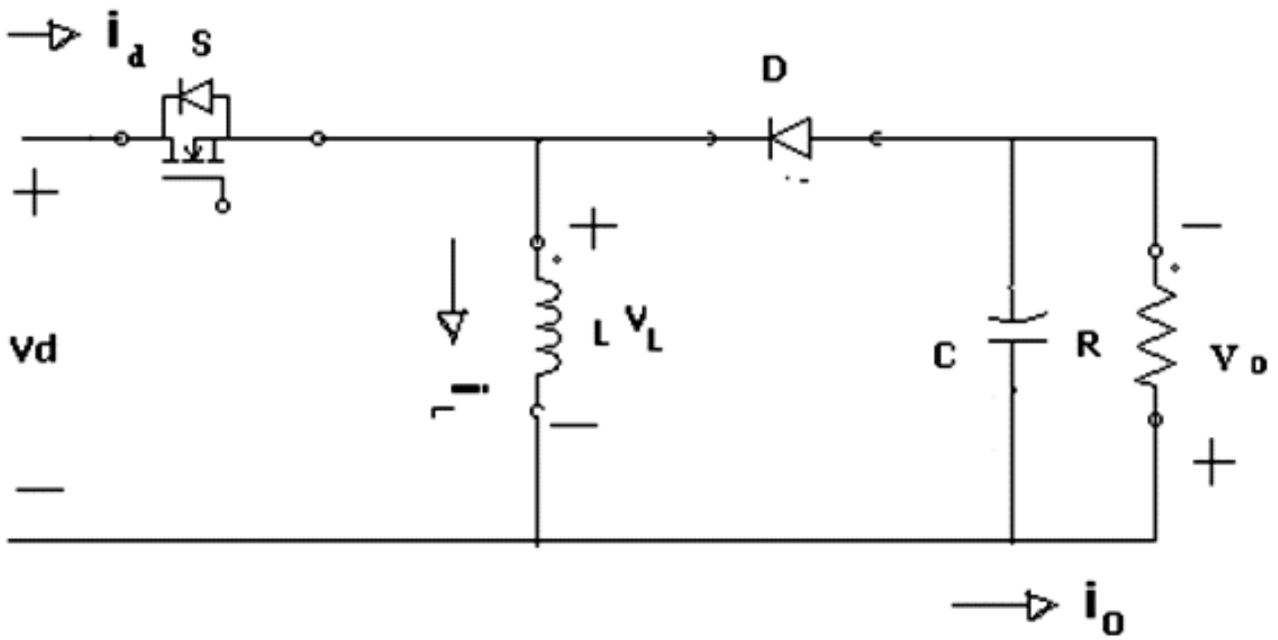

Fig. 7. Buck Boost converter

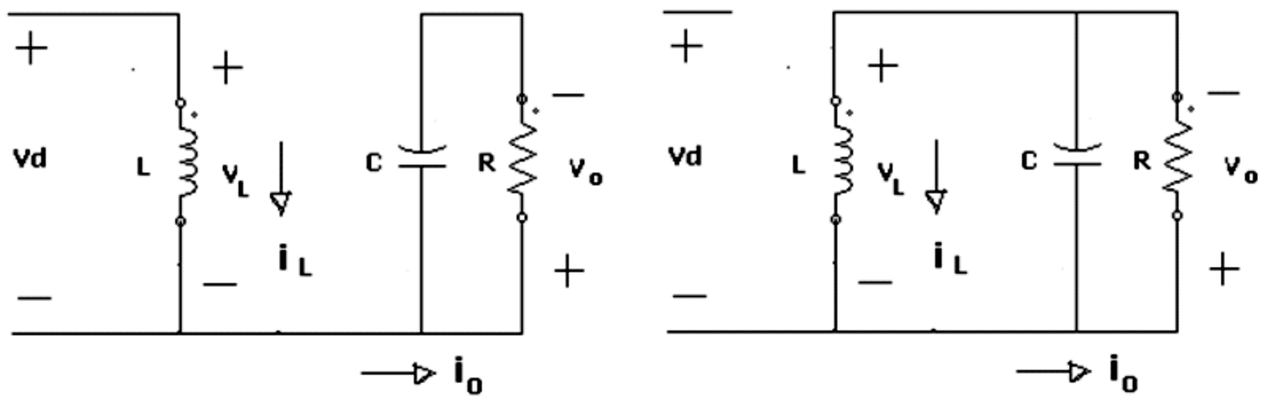

Fig. 8 (a) [8]. Buck Boost converter in switch on and switch off modes

stored in the inductor is transferred to the load and is also used to charge the capacitor.

The discontinuous mode of operation is a function of four parameters such as decrease of load current, inductance, duty ratio and switching frequency. Except the duty ratio, the other parameters can be lumped into a single dimensionless parameter K where

$$K = \frac{2L}{RT} \quad ...(2)$$

The reduction value of K leads to the discontinuous mode of operation.

From the volt second balance of the inductor

$$\frac{V_o}{V_d} = \frac{D}{\sqrt{K}} \quad ...(3)$$

The regulator will operate in discontinuous conduction mode when

$$\Delta I < (1 - D) \text{ and } K < (1 - D)^2 \quad ...(4)$$

where ΔI is the falling time of the inductor current as shown in Fig. 8 (b).

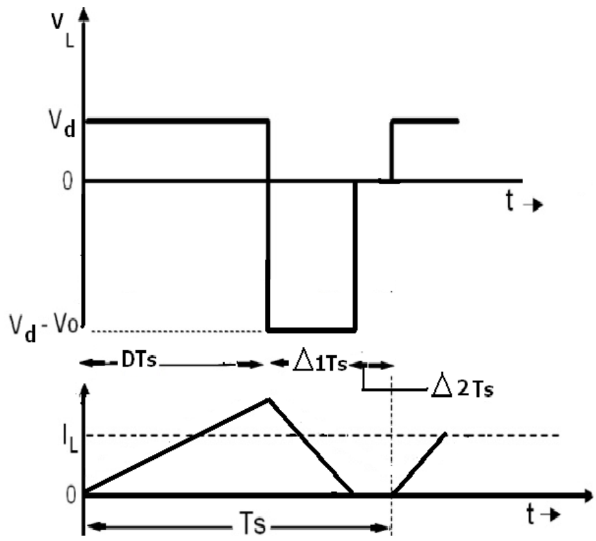

Fig. 8 (b) [8]. Discontinuous conduction mode-waveforms of a buck boost converter

In this work, a complete analysis of the ac/dc step up converter is presented in section IV. The various operational modes are discussed in section IV A. The relation between the switching frequency, duty cycle and various parameters of the circuit has been derived in section IV B. The simulation circuit with closed loop control scheme and simulation results are presented in section IV C.

IV. DIRECT AC/DC STEP UP CONVERTER

The proposed converter shown in Fig. 9 consists of a boost converter connected in parallel with a buck boost converter. The boost converter consists of an inductor L1, switch S1, diode D1 and the buck boost converter consists of inductor L2, switch S2, diode D2. The output capacitor is charged by the boost converter during the positive half cycle and by the buck boost converter during the negative half cycle of the sinusoidal input voltage obtained from the micro generator. Since the output of the micro electromagnetic generator is an ac voltage, it is being modeled as an ac source. Here the negative voltage gain of the buck boost converter is used to obtain the dc output voltage during the negative half cycle of the sinusoidal input voltage.

A. Modes of operation of proposed converter

There are four modes of operation of the proposed converter [1]. Mode 1 and mode 2 operate during positive half cycle of the input voltage and mode 3 and mode 4 operate during the negative half cycle of the sinusoidal input voltage.

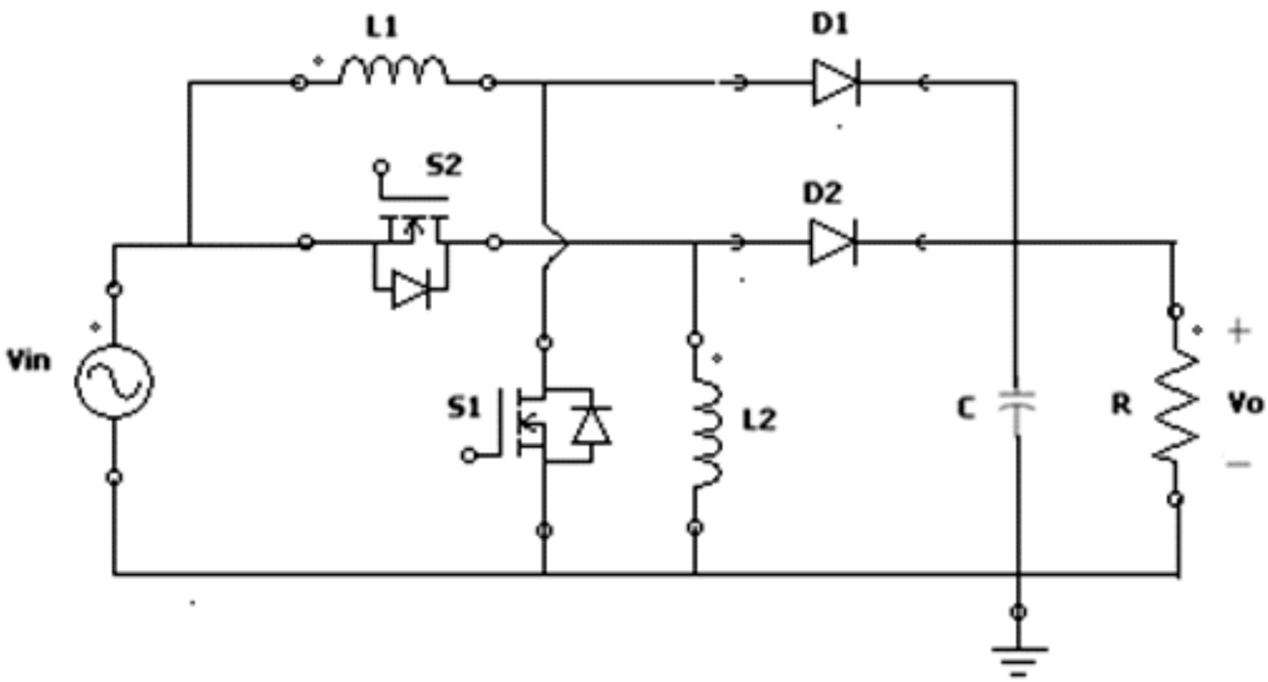

Fig. 9 [2]. Proposed AC/DC step up converter

Mode 1

In this mode, since the input voltage is positive, the boost converter operates. When the gate pulse of boost converter is high, switch S1 is on, the inductor L1 stores its energy through the switch S1 as shown in Fig. 10. The inductor current increases from zero as shown in Fig. 6 (b).

Mode 2

During positive half cycle, when the switch S1 is off, the diode D1 becomes forward biased and the inductor L1 supplies its energy along with the supply voltage to the load as shown in Fig. 11. The inductor current decreases and becomes zero as shown in Fig. 6 (b).

Mode 3

During the negative half cycle of the sinusoidal input voltage, buck boost converter operates. When the gate pulse of the buck boost converter is high, the switch S2 is on, the inductor L2 stores its energy as shown in Fig. 12. The inductor current increases as shown in Fig. 8 (b). The capacitor discharges through the load.

Mode 4

During the negative half cycle, when the switch is off (as the gate pulse to the buck boost converter is low), the diode D2 becomes forward biased, the inductor supplies its energy through the load and also charges the capacitor C as shown in Fig. 13. The inductor current starts to decrease and it becomes zero and tends to become negative. Since the diode is an unidirectional element, it does not allow the inductor current to flow in the opposite direction.

B. Circuit design

The circuit is designed for supplying 55 mW of power to the load with an input voltage of 400 mV which is the output of micro electromagnetic generator. The output voltage is selected to be 3.3V in order to supply the electronic load. The inductor values and the duty cycle of both the boost and buck boost converters are assumed to be equal. The switching frequency is selected to be 20 kHz.

For the boost converter with DCM, the inductor value can be calculated from equation (5)

$$\Delta I = \frac{V_{in} \times t_{on}}{L} \qquad ...(5)$$

Where ΔI is the ripple current for an input voltage of V_{in} and an output voltage V_{out} for a frequency f

where

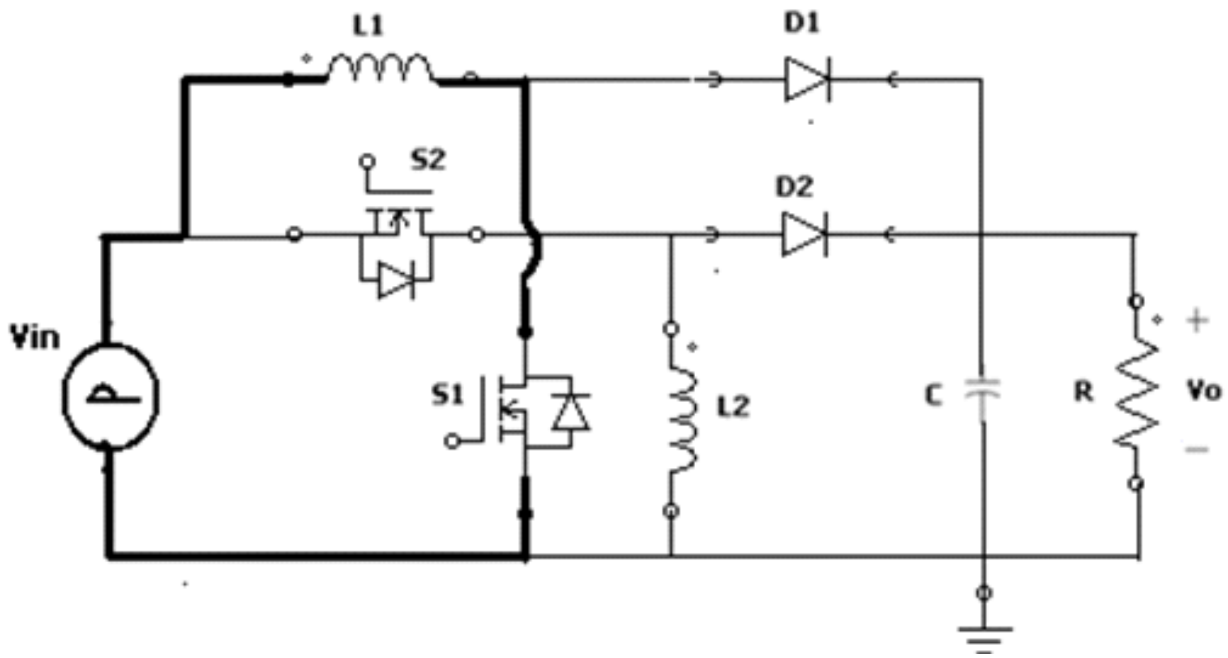

Fig 10. Mode1 [1] (Gate pulse of S1 high & Gate pulse of S2 low)

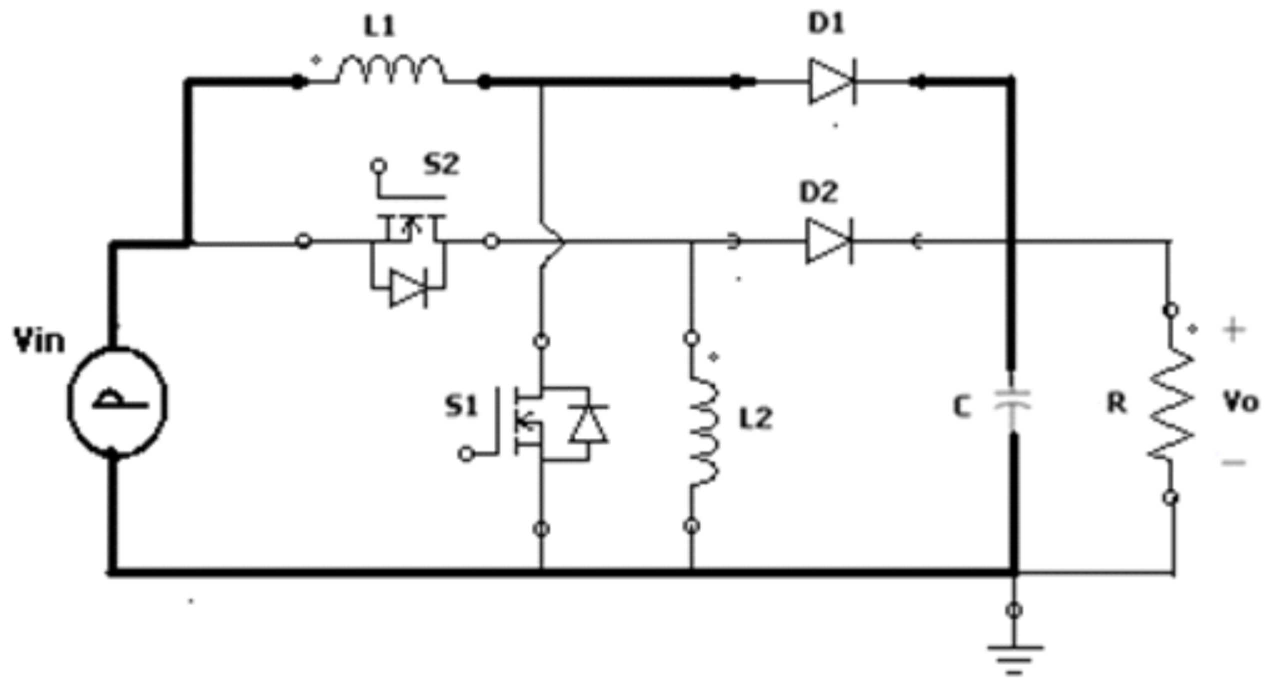

Fig. 11 [1]. Mode 2 (Gate pulse of S1 low & Gate pulse of S2 low)

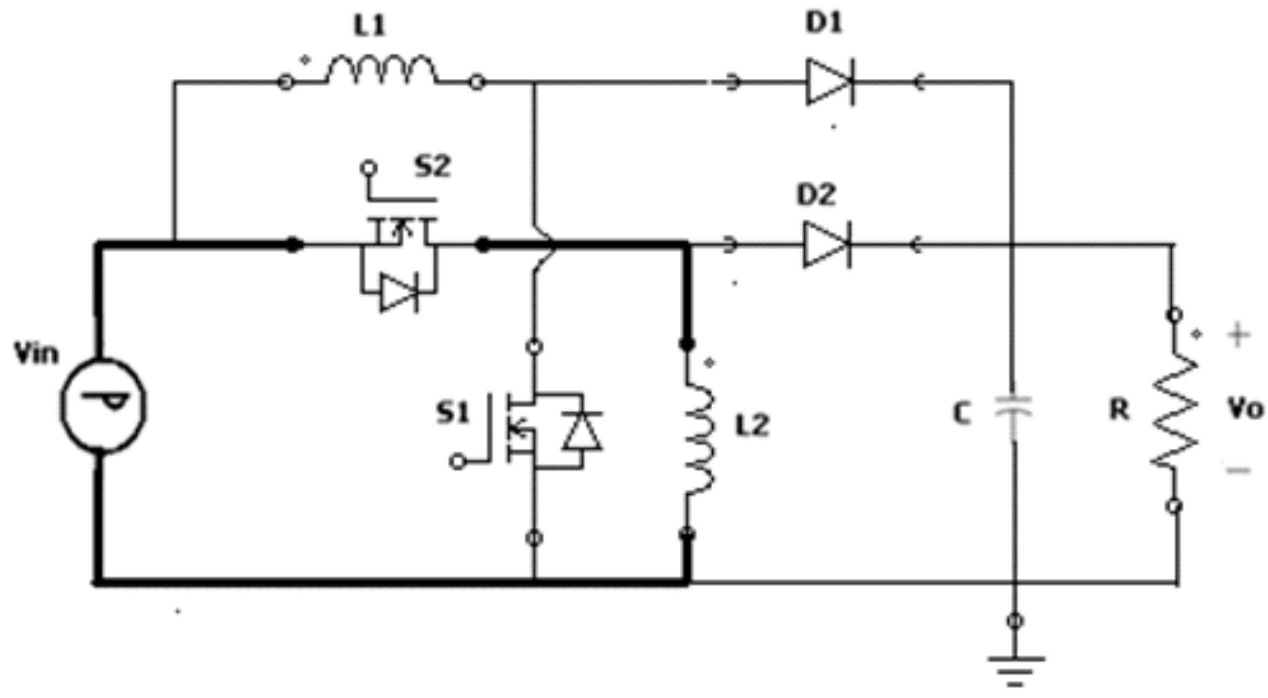

Fig. 12 [1]. Mode 3 (Gate pulse of S1 low & Gate pulse of S2 high)

$$\frac{1}{f} = T = t_{on} + t_{off} \quad ...(6)$$

The inductor value is obtained as 4.7 μ H. The capacitor value is obtained from (7)

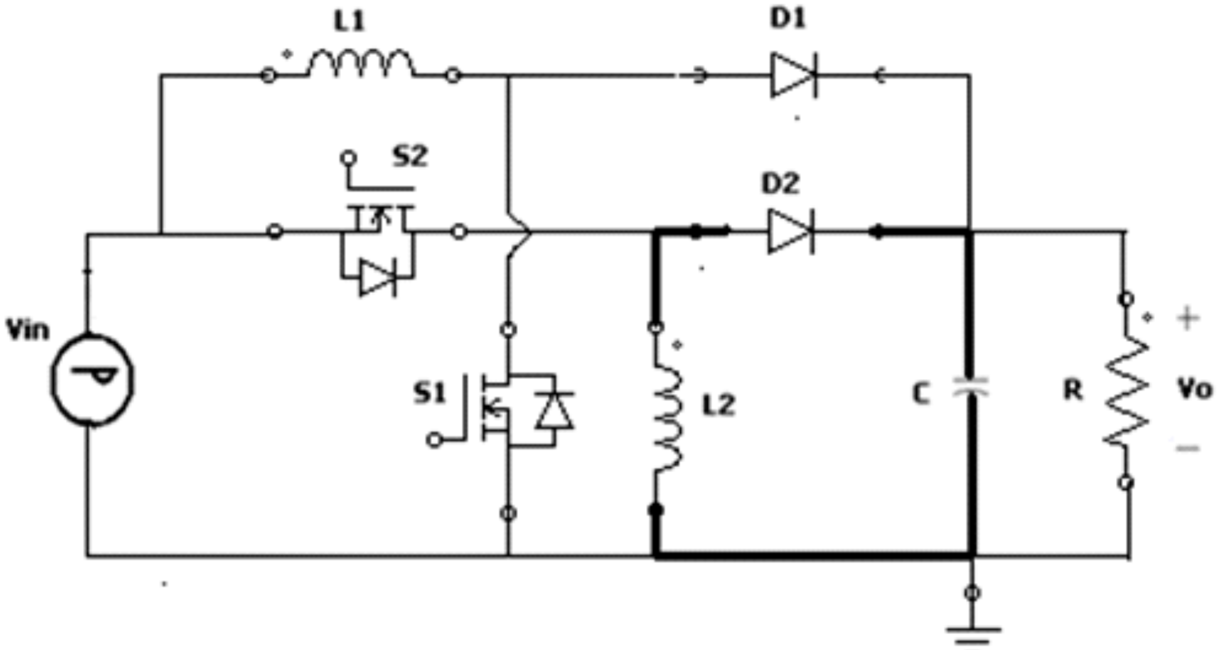

Fig. 13 [1]. Mode 4 (Gate pulse of S1 low & Gate pulse of S2 low)

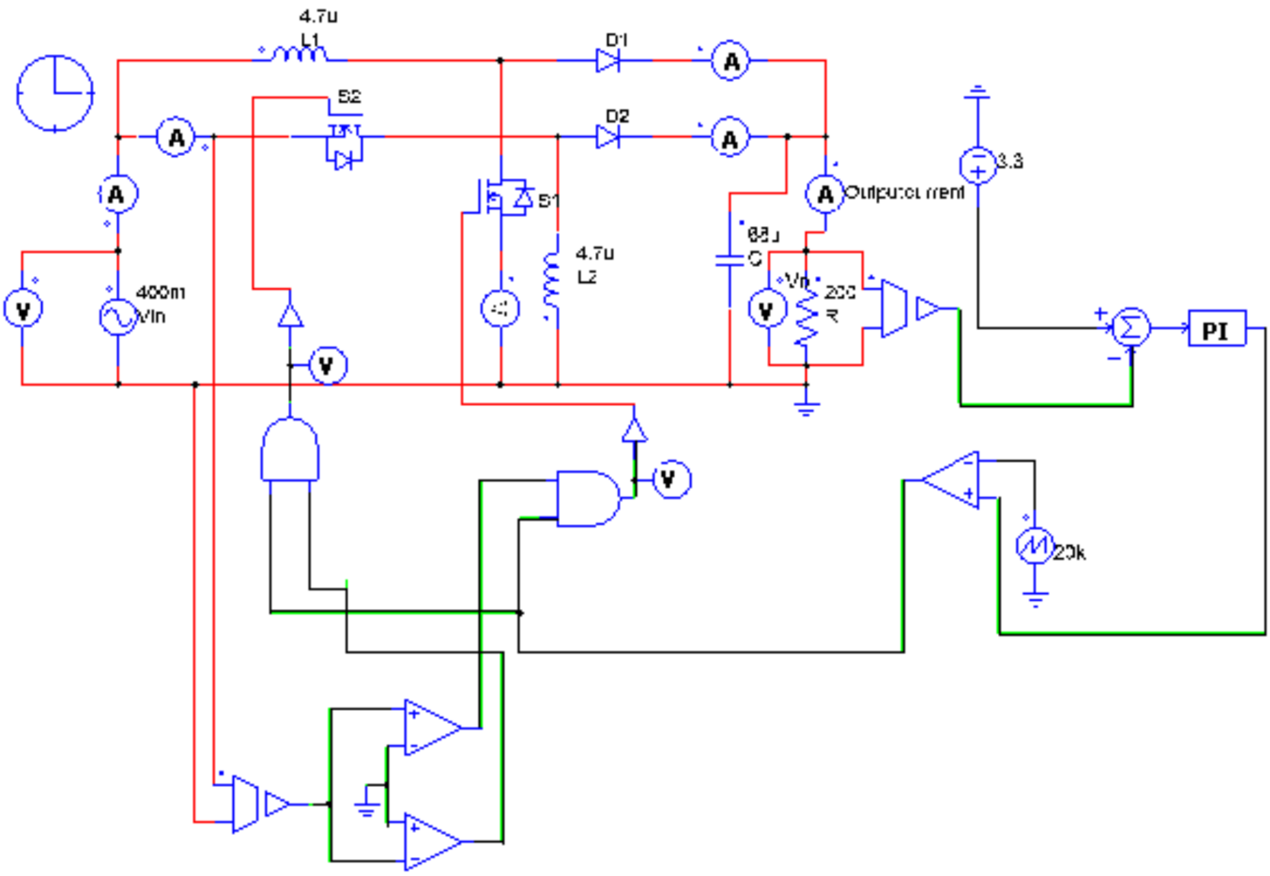

Fig. 14 Simulation circuit of the proposed converter

$$C \geq \frac{I_{o\,max} \times \left[1 - \frac{2L}{RT_s}\right]}{f \times \Delta V_c} \quad ...(7)$$

The output current is calculated from (8)

$$I_o = \frac{P}{V_o} \quad ...(8)$$

The inductor value for buck boost converter is also chosen to be 4.7 μ H. The value of the resistor is obtained from (9).

$$R = \frac{V_o}{I_o} \quad (9)$$

C. Simulation circuits and Simulation results

With these design values, the power circuit and the control circuit have been simulated in power electronic software PSIM© and satisfying results have been obtained.

The closed loop control has been implemented in the simulation. The simulation circuit is shown in Fig.

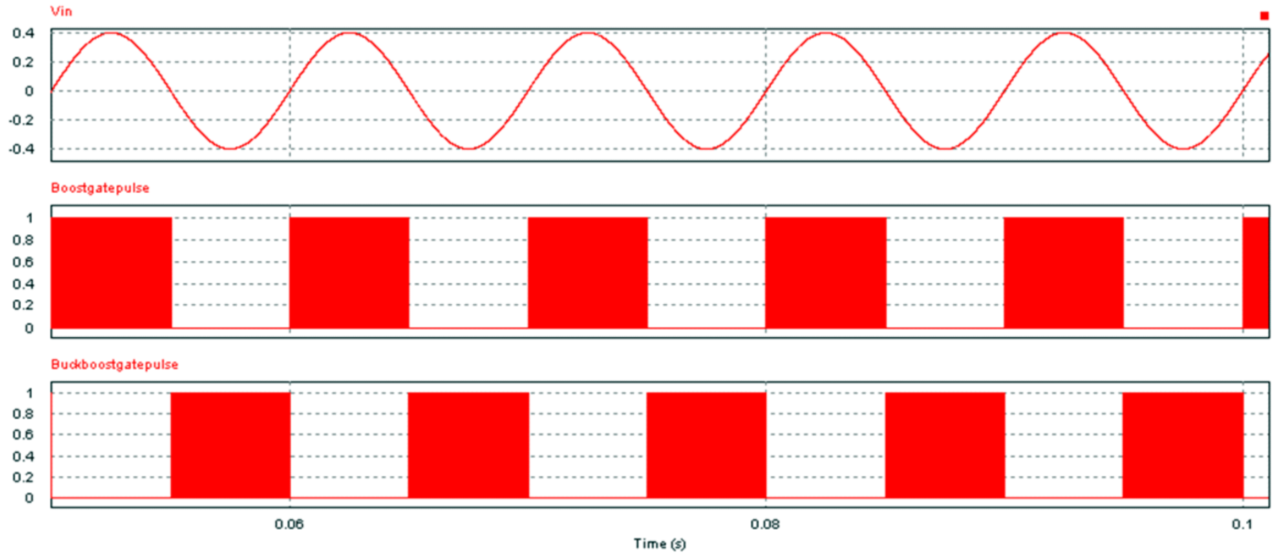

Fig. 15. (a) Variation of input voltage with time (b) boost gate pulses (c) buck boost gate pulses

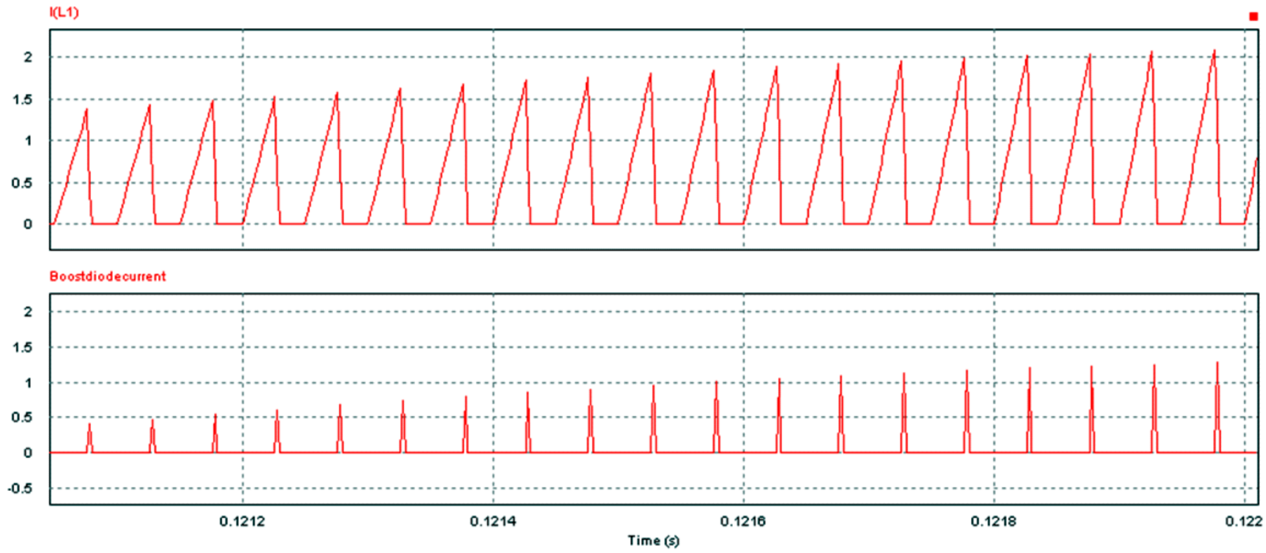

Fig. 16. (a) Variation of boost inductor current with time (b) Variation of boost diode current with time

12. The reference output voltage is set as 3.3 V as required for an electronic load. The micro electromagnetic generator is modeled as an ac source with a voltage of 400 mV. The electronic load is modeled as a resistor.

The feedback from the output is taken and is compared with the reference value and the error is fed to PI controller and the output of the PI controller is compared with the saw tooth waveform and PWM signals are obtained. The gate of the MOSFETs are being switched on by the PWM output based on the output of the zero crossing detector.

The various waveforms obtained are shown in Fig. 15-19. The gate pulses of boost and buck boost converter switches are shown in Fig. 15. The discontinuous conduction of boost and buck boost converters can be clearly observed from Fig. 16 & Fig. 17. The input voltage is an ac voltage with a magnitude of 400 mv and the output voltage is a regulated dc voltage which settles at 3.28 V as shown in Fig. 18.

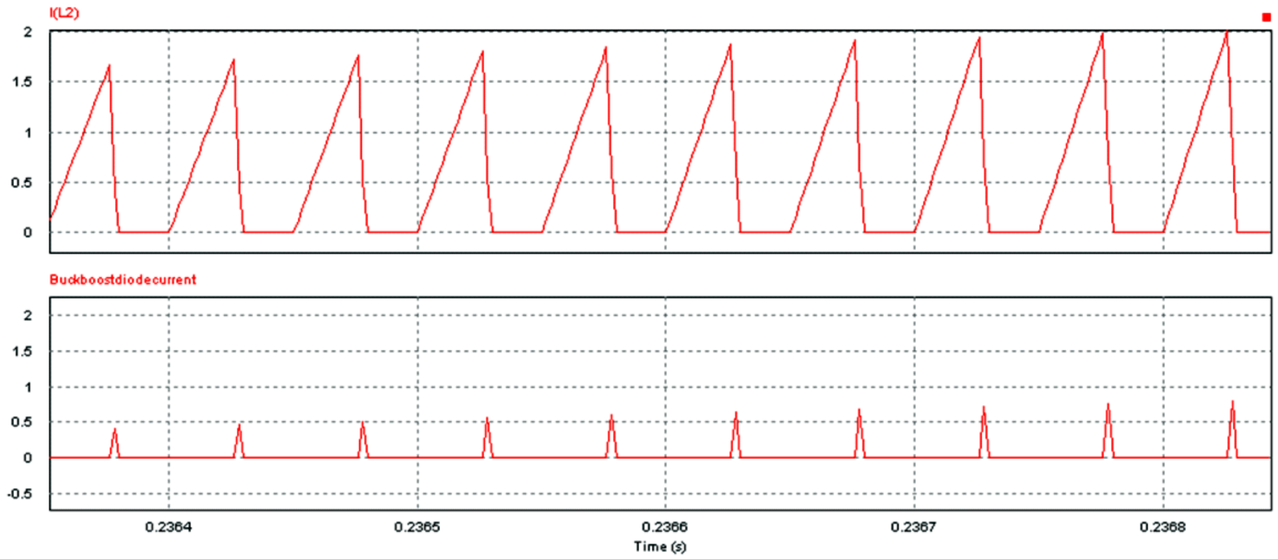

Fig. 17. (a) Variation of buck boost inductor current with time (b) Variation of buck boost diode current with time

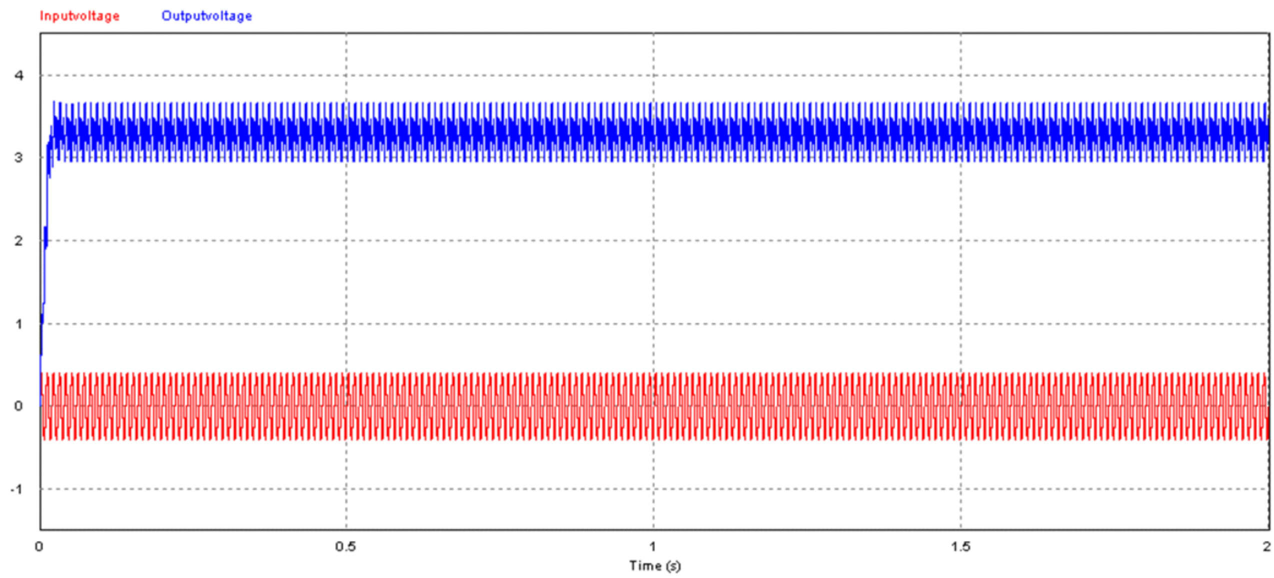

Fig. 18. (a) Variation of output voltage with time (b) Variation of input voltage with time

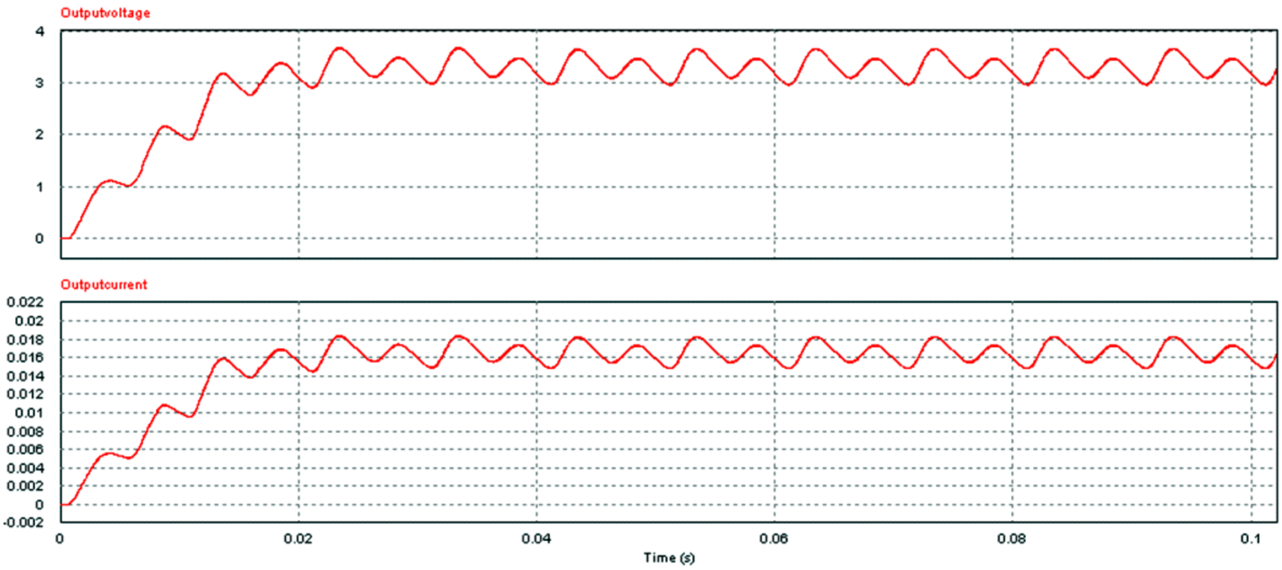

Fig. 19. (a) Variation of output voltage with time (b) Variation of output current with time.

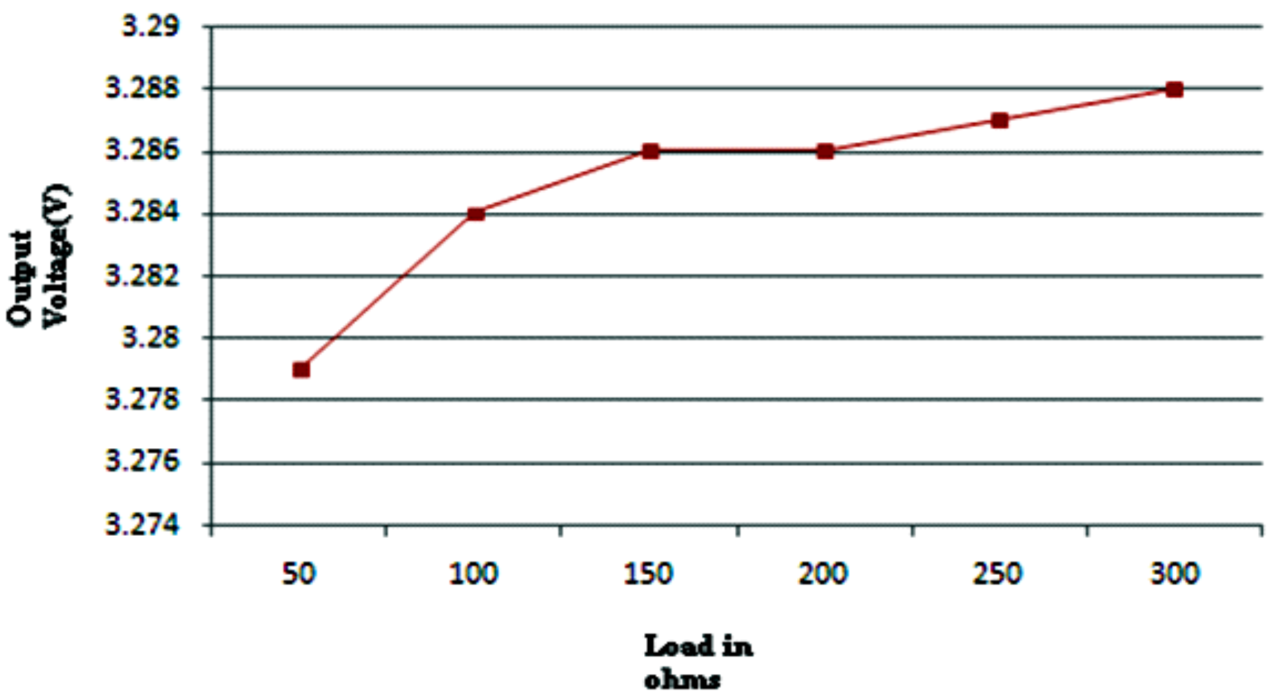

Fig. 20. Variation of output voltage with load

The output current also settles at 0.016 A as shown in Fig. 19. Even when the load is varied widely from 50 Ω upto 300 Ω the output is found to be varied 3.279 to 3.288 as shown in Fig. 20.

V. CONCLUSION

An ac/dc step up converter using boost and buck boost converters which operate during positive and negative half cycles respectively and supplies a load of 55 mW has been designed, simulated successfully.

The low voltage energy harvesting is achieved here since the input supply to this converter is from a micro generator which scavenges the energy from ambient sources.

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