Simulation of a Vibration Based Green Energy Harvesting System

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***Abstract* —This paper presents the simulation of the mathematical model of an electromagnetic micro generator which converts vibration into electrical energy. The output of the micro generator is of the order of millivolts and is an ac voltage. It has to be converted to dc as well as stepped up into a higher voltage as required by an electronic load. This is achieved by a step up converter where a direct ac/dc conversion takes place. A closed loop control is incorporated so that the output is maintained even when the input voltage is changed.**

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 requirement of electronic devices such as wireless sensors, medical implants etc. has been considerably reduced due to the developments of the highly efficient semiconductor devices. 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 [4]–[6]. 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.

Conversion of ambient mechanical vibration into electrical energy is a field of attraction for many researchers. An analytical model which predicts the performance of electromagnetic harvester based on the knowledge of acceleration is designed [4]. Using MEMS technology, a system incorporating electrostatic motion driven generator for low frequency motion is developed [5]. Buck boostconverter is incorporated for low voltage energy harvesting using vibration based piezoelectric generators are designed with MEMS technology [6]. A design incorporating a variable capacitor to power low power electronic devices is developed using MEMS technology [7]. An energy allocation algorithm with predictable energy inputs has been developed for the realization of networks composed of energy harvesting devices [10]. A model has been developed for converting radio frequency waves from air to electrical energy [11].

In this work, the micro electromagnetic generator which consists of a permanent magnet, copper coils and a spring as shown in Figure. 1, is taken as the energy source. In this micro generator, 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. The voltage generated by the micro generator depends upon the number of turns of coil and the magnetic structure.

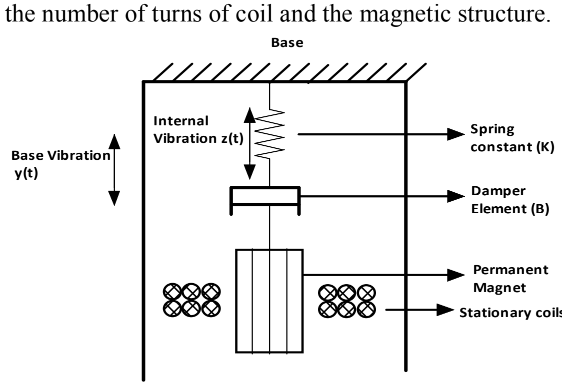

Figure. 1. Micro electromagnetic generator

Since the ac voltage generated by the micro electromagnetic generator is very small which is of the order of a few hundred milli 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 voltage and also to store the electric power in the power storage elements.

The block diagram for low voltage energy harvesting is shown in Figure. 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. There are two stages involved in this conversion process. They are rectification and boosting processes [5]. 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 Figure. 3.

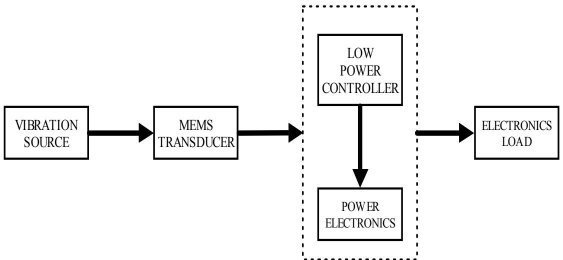

Figure. 2. Block diagram for low voltage energy harvesting.

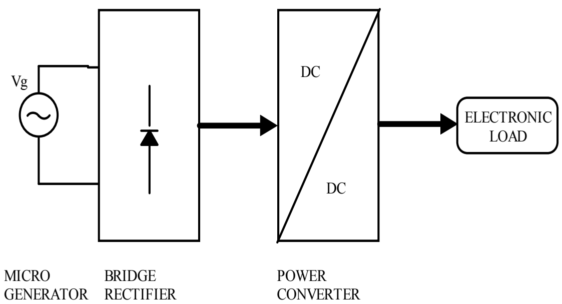

Figure. 3. Conventional power converter

The main disadvantage in this two stage topology is that since the output of micro generators is very low, rectification is not possible with the conventional diodes. 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 [2].

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 which results in a higher efficiency. The block diagram for low voltage energy harvesting with an ac/dc step up converter is shown in Figure. 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. 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 converters in DCM are (a) the implementation of control scheme is easier and (b) switching losses of converter can be reduced.

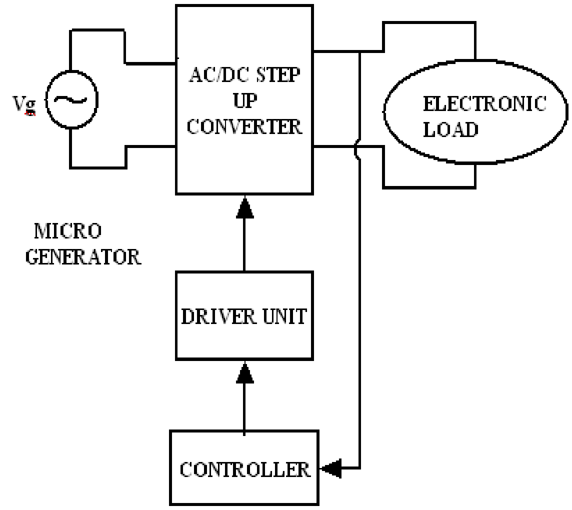

Figure. 4. Block diagram for low voltage energy harvesting with an ac/dc step up converter.

The rest of the work is organised as follows. The mathematical modeling of the micro generator is done in section II. A complete analysis of the ac/dc step up converter is presented in section III. The various operational modes are discussed in section III A. The relation between the switching frequency, duty cycle and various parameters of the circuit has been derived in section III B. The simulation circuit with closed loop control scheme and simulation results are presented in section III C.

II. MODELING OF MICROGENERATOR

The output of electromagnetic micro generator is 400mV. The input to the micro generator is sinusoidal vibration with an amplitude of 0.2m and with a frequency of 108 Hz. When the vibration is given to the base, the spring and permanent magnet experiences an internal vibration with respect to the housing. This will result in the rate of change of flux linkages thereby an emf is generated at the coil terminals. The base vibration is represented by *y(t)*. The internal vibration which is experienced by the permanent magnet, damper and the spring is represented by *z(t)*. The spring constant is represented by *K*, the damper element is represented by *B* and permanent magnet is represented by mass *m*. From Figure. 1, the mathematical modeling of micro generator can be done [1] as follows. The EMF E_i of the micro generator can be obtained as

$$E_i = n\frac{\partial \emptyset}{\partial t} = n\frac{\partial \emptyset}{\partial z}\frac{\partial z}{\partial t} = n\frac{\partial \emptyset}{\partial z}z'$$

$$\therefore E_i = C_E z' \qquad (1)$$

Where $C_E = n\frac{\partial \emptyset}{\partial z}$ represents the electromechanical constant which depends upon the number of turns of the coil and magnetic structure.

The mathematical model from Figure. 1 can be written as

$$my''(t) = mz''(t) + Bz'(t) + Kz(t) \quad (2)$$

$$y''(t) = z''(t) + \frac{B}{m}z'(t) + \frac{K}{m}z(t) \quad (3)$$

Here, the mechanical work is converted into electrical energy by damper. The electrical power P_e is obtained as

$$P_e = E_i \times i \quad (4)$$

The mechanical power P_m is given by rate of doing work.

$$P_m = \frac{dW}{dt} = F \times v \quad (5)$$

The damping force F_B is responsible for the energy conversion.

$$\therefore F_B \times v = E_i \times i \quad (6)$$

From equation (1)

$$F_B \times z' = C_E z' \times i = n\frac{\partial\phi}{\partial z}z' \times i \quad (7)$$

$$F_B = n\frac{\partial\phi}{\partial z} \times i \quad (8)$$

Since $F = ma$, from equation (8)

$$z'' = (n\frac{\partial\phi}{\partial z} \times i) \div m = (C_E/m) \times i \quad (9)$$

From equation (3), *α1* is given by *K/m*, *α2* is given by *B/m* and α3 is given by C_E/m. From equations (3), (7) & (9), the electromagnetic micro generator can be modeled as shown in Figure. 5.

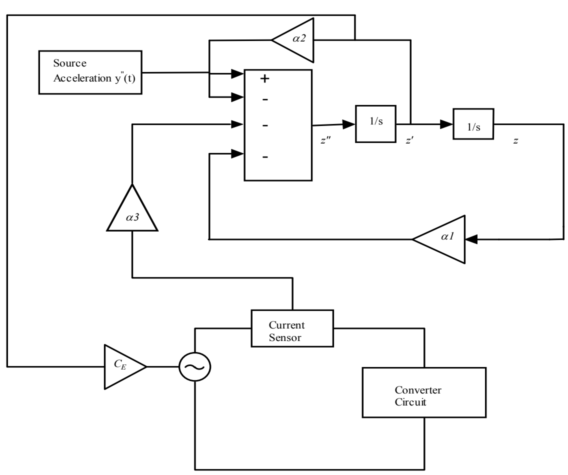

Figure. 5. Mathematical model of an electromagnetic micro generator

III. AC/DC STEP UP CONVERTER

The proposed converter shown in Figure. 6 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 C 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. 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.

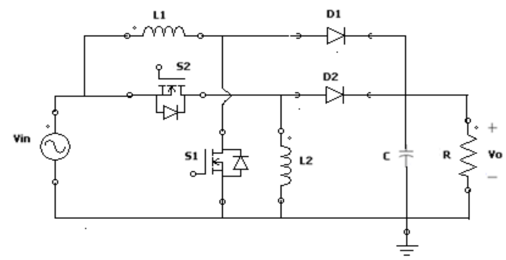

Figure. 6 [2]. Proposed AC/DC step up converter

A. Modes of operation of proposed converter

There are four modes of operation of the proposed converter [2]. 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.

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 Figure. 7. The inductor current increases from zero as shown in Figure. 8.

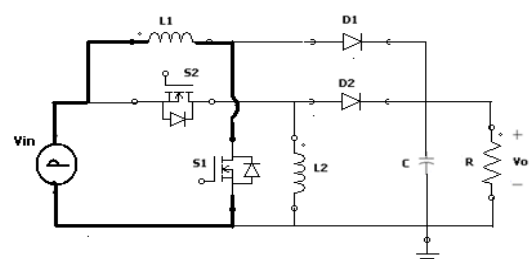

Figure. 7. Mode 1 [2] (Gate pulse of S1 high & Gate pulse of S2 low)

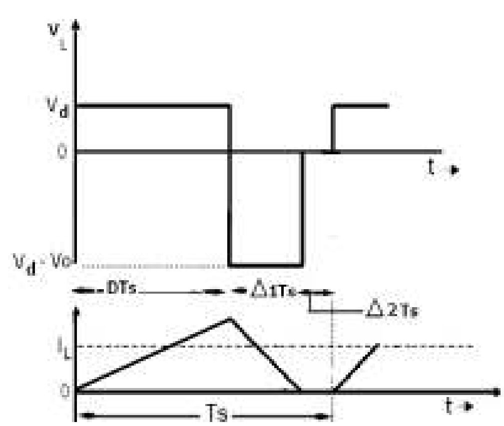

Figure .8 [9]. Discontinuous conduction mode-waveforms of a boost converter

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 Figure. 9. The inductor current decreases and becomes zero as shown in Figure. 8.

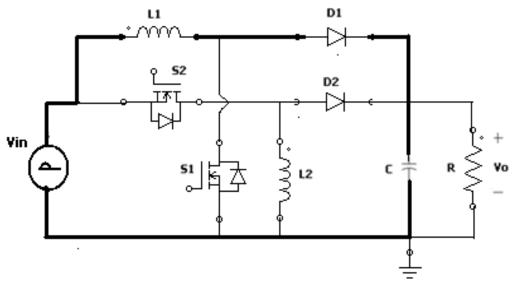

Figure. 9 [2]. Mode 2 (Gate pulse of S1 low & Gate pulse of S2 low)

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 Figure. 10. The inductor current increases as shown in Figure. 11. The capacitor discharges through the load.

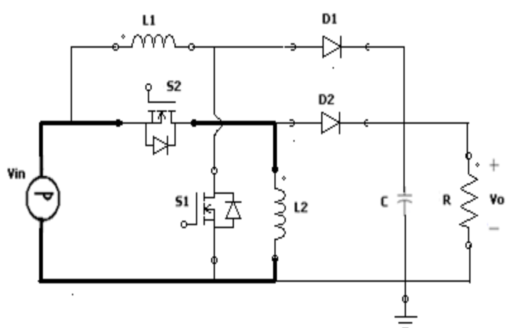

Figure. 10 [2]. Mode 3 (Gate pulse of S1 low & Gate pulse of S2 high)

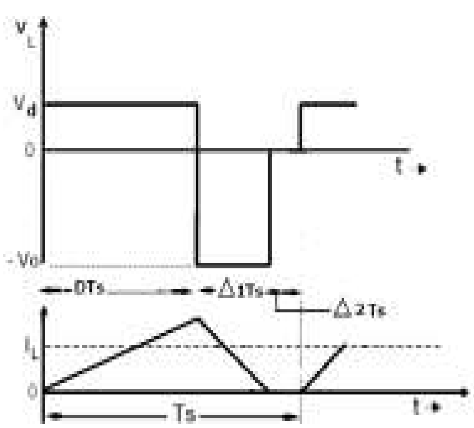

Figure. 11 [9]. Discontinuous conduction mode-waveforms of a buck boost converter

Mode 4:

During the negative half cycle, when the switch is off (as the gate pulse to the buck boost converter is low),

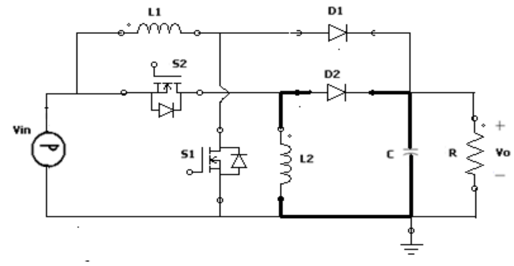

Figure. 12 [2]. Mode 4 (Gate pulse of S1 low & Gate pulse of S2 low)

the diode D2 becomes forward biased, the inductor supplies its energy through the load and also charges the capacitor C as shown in Figure. 12. 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 55mW of power to the load with a peak to peak input voltage of 800mV 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 as 50 kHz. For the boost converter with DCM, the inductor value can be calculated from equation (10)

$$\Delta I = \frac{V_{in} \times t_{on}}{L} \qquad (10)$$

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

$$\text{where } \frac{1}{f} = T = T_{on} + T_{off} \qquad (11)$$

The inductor value is obtained as 4.7µH. The capacitor value is obtained from (12) as 68µF.

$$C \geq \frac{I_{omax} \times \left[1 - \sqrt{\frac{nL}{RT_s}}\right]}{f \times \Delta V_c} \qquad (12)$$

The output current is calculated from (13)

$$I_o = \frac{P}{V_{out}} \qquad (13)$$

The inductor value for buck boost converter is also chosen to be 4.7µH. The value of the resistor is obtained from (14).

$$R = \frac{V_{out}}{I_o} \qquad (14)$$

C. *Simulation circuits and Simulation results*

The micro electromagnetic generator is modeled and simulated in Power Electronic software PSIM© as shown in Figure. 13. With the design values, the power circuit and the control circuit have also been simulated and satisfying results have been obtained.

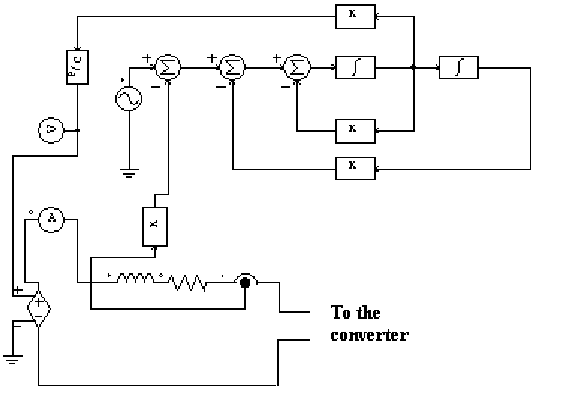

Figure. 13. Simulation circuit of mathematical model of the electromagnetic micro generator.

The values of *α1, α2, α3*& C_E have been calculated from parameters of electromagnetic micro generator [1]. The input source acceleration with a magnitude of 0.2m and a frequency of 108 Hz as shown in Figure. 14, is given as an input to the generator. It can produce a peak to peak output voltage of 800 mill volts as shown in Figure. 15.

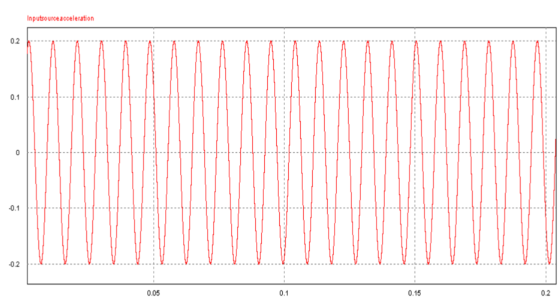

Figure. 14. Input source acceleration

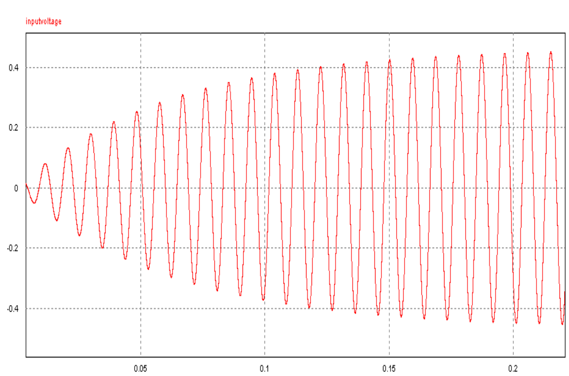

Figure. 15. Micro generator output voltage

The rms value of the micro generator output current was found to be 1.28A.

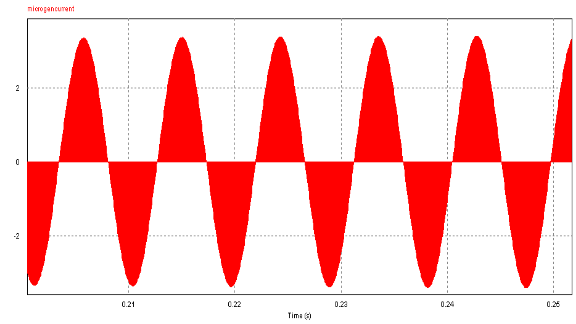

Figure. 16. Micro generator output current

The closed loop control has been implemented in the simulation. The simulation circuit of the converter part is shown in Figure. 17. The reference output voltage is set as 3.3V as required for an electronic load. The electronic load is modeled as a resistor.

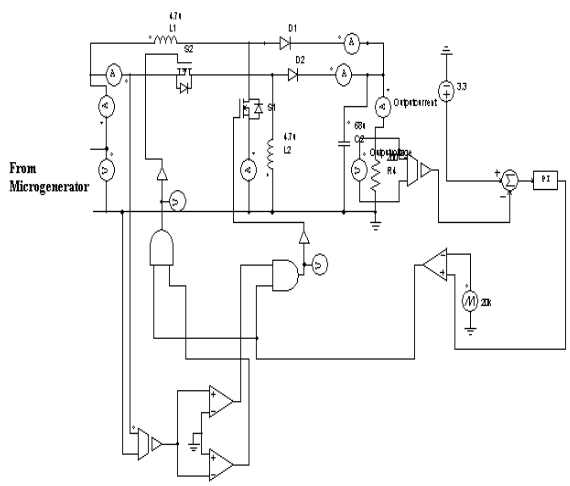

Figure. 17. Simulation circuit of the proposed converter

The discontinuous conduction of boost and buck boost converters can be clearly observed from Figure. 18 & Figure. 19. 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 saw tooth waveform and the PI controller output as shown in Figure. 20.

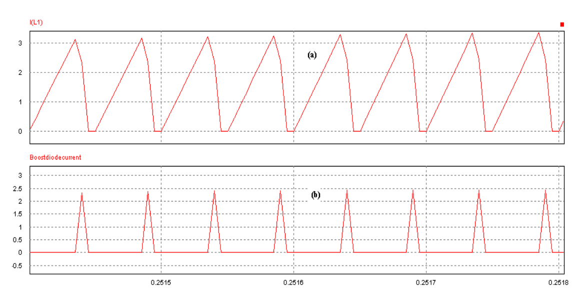

Figure. 18. (a) Variation of boost inductor current with time (b) Variation of boost diode current with time

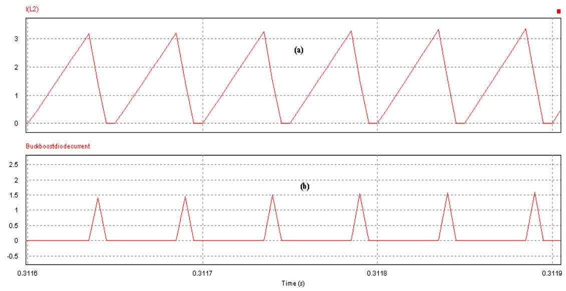

Figure. 19. (a) Variation of buck boost inductor current with time (b) Variation of buck boost diode current with time

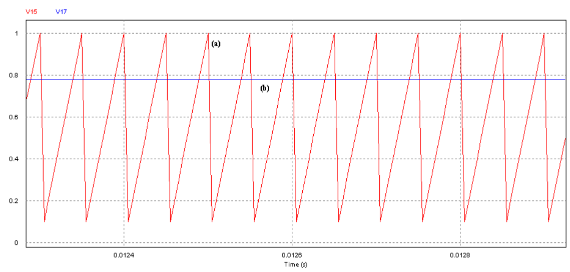

Figure. 20. (a) Saw Tooth Waveform (b) PI controller output

The gate pulses of boost and buck boost converter switches are shown in Figure. 21. The gate of the MOSFETs is switched on by the PWM output based on the output of the zero crossing detector.

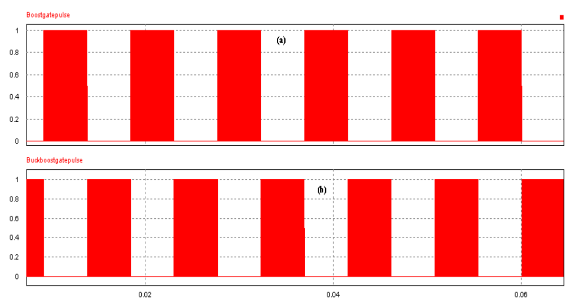

Figure. 21. (a) Boost gate pulses (b) Buck boost gate pulses

The input voltage of the converter is an ac voltage with a peak of 400mV and the output voltage is a regulated dc voltage which settles at 3.16V as shown in Figure. 22. (a). The output current also settles at 0.0158A as shown in Figure. 22. (b).

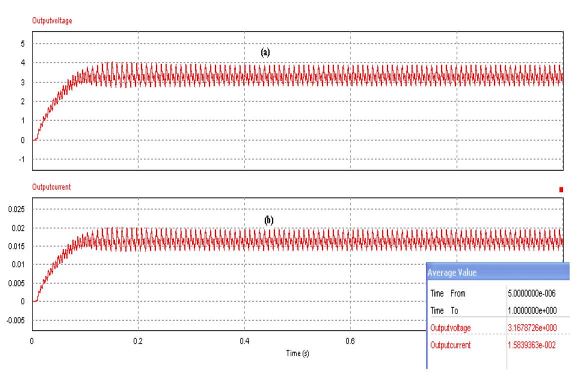

Figure. 22. (a) Variation of output voltage with time (b) Variation of output current with time

IV. Conclusion

The low voltage energy harvesting is achieved here since the input supply to this converter is from an electromechanical micro generator which scavenges the energy from ambient sources such as vibration. An ac/dc step up converter using boost and buck boost converters which operate during positive and negative half cycles respectively has been designed and simulated successfully. It has been found that when the peak input voltage is varied from 373mV to 446mV the average value of output voltage varies from 3.02V to 3.16V.

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