

Analysis of Low Voltage Bridgeless AC DC Energy Conversion

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Abstract: The energy source for energy harvesting micro-generators is present as ambient background. Energy harvesting micro generator provide a very small amount of power for low-energy electronic devices. This paper presents the analysis of electromagnetic resonant micro-generator for the low voltage bridgeless AC DC energy conversion. The proposed converter model uses parallel connected boost and buck-boost converters to step up and rectify the low AC voltage fed from the micro-generator output to higher DC voltage to be fed to an electronic load. The positive and negative half cycle of the AC voltage obtained by the micro-generator is processed by the boost and the buck-boost converters respectively. Detailed analysis of the boost and the buck boost converter of the proposed model are carried out to suit the specifications of the micro-generator output and the load.

Keywords: micro-generator, boost converter, low voltage, AC DC energy conversion, boost converter, MOSFET.

I. INTRODUCTION

All portable electronic devices are powered by batteries [24], [34]. Energy harvesting from environmental or human sources has proven to be implemented effectively in battery driven devices [7], [24]. Many types of micro-generators are used in the self-powered devices and many of them are reported in various literary works for harvesting energies in different forms [7]-[12], [15], [18], [20]-[22]. The electromagnetic micro-generators have the highest energy density and in the presented AC DC bridgeless converter, energy is extracted from an electromagnetic system [3], [5], [30], [44]. The electromagnetic generators are spring mass damper based systems where small magnitude ambient mechanical vibrations are amplified and the motion is converted to electrical energy by electromagnetic coupling [3], [29]. The micro-generator used is one such electromagnetic system [10], [18]. There are many micro-generators, which harvest mechanical energies from the ambient and they are currently the focus of many research groups [11]-[15]. The Fig. 1 shows the block diagram of an energy harvesting system.

The inertial micro-generators have different energy conversion principles and hence they can be classified into three major types that are [3], [25]:

- Electromagnetic
- Electrostatic
- Piezoelectric

In the electromagnetic micro-generator, mechanical energy is converted into electrical energy by electromagnetic coupling [30]. Just as electromagnetic generators, the micro-scale electrostatic or capacitive forces have become quite significant and several methods have been devised to generate electrical energy from capacitive sources [25]. A piezoelectric material can produce an electric potential, high voltage (low current) when it is put under strain that can be either compressing or deflecting [21], [3], [15], [18], and [29]. Conventional

power processing circuits that consist of two stages bridge rectification have been developed earlier for energy harvesting but, these converters proved be inefficient for the micro volts application. To address this problem, direct converters were proposed where bridge rectification is avoided and single stage boost converters were used for the stepping up of low voltages [13], [16], [18], [35]-[37]. A direct method for AC DC conversion is presented in [2], [5] that form the basis of the proposed converter. A direct AC DC converter is used for efficient energy harvesting from the low voltage micro generator output to voltage that can be fed to the electronic load. This converter avoids the use of bridge rectifiers, and directly converts the AC input to the required DC output. The converter utilizes a boost converter and a buck-boost converter that operate in parallel with each other to process the positive and the negative half cycles of the AC input voltage.

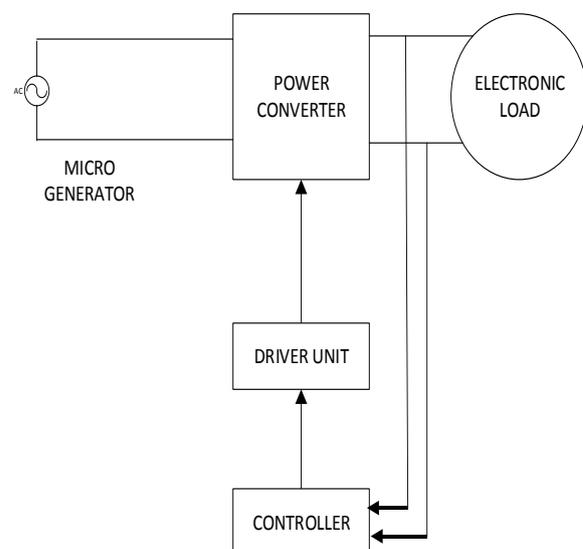


Fig 1 Block diagram for low voltage energy harvesting with power converter

The paper is organized in IV different sections. The section I gives a brief introduction of the previous literary works done in the field of low voltage energy harvesting. Section II presents the detailed analysis of the electromagnetic micro-generator. The III section describes and analyses the proposed converter topology for low voltage bridgeless AC DC energy conversion. Section IV gives the modelling, simulation and the results of the proposed converter topology. The low voltage AC from the micro-generator output is efficiently rectified and stepped up to a higher magnitude DC voltage.

II. ANALYSIS OF ELECTROMAGNETIC MICRO-GENERATOR

An Electromagnetic generator uses the permanent magnet and coil arrangement for damping purpose. It can also be called as the VDRG or the velocity damping resonant generator since, the damping force is opposing the proof mass integral velocity and it is best suited for sources that have high frequency and low amplitude. The optimal damping factor ζ is given by

$$\zeta = \frac{Y_0}{2Z_1}$$

Where, Y_0 = source vibration amplitude
= 25 μ m

And Z_1 = 1mm

In this case, ζ = 0.0125

The power extracted is hence given by:

$$P_D^{opt} = \frac{v^2}{2D} = \frac{(\omega Z_1)^2 (2m\omega_n \zeta)}{2}$$

Where v = proof mass velocity

D = damping coefficient

ω_n = resonating frequency, where frequency f in Hz is 322Hz

m = proof mass = 0.5 g

The power obtained from the above damper based system is 52mW.

The Fig. 2 depicts a typical inertial electromagnetic micro-generator. A key design choice to process the power circuit is the current and the corresponding voltage at which the power has to be extracted for rectification. To minimize the conduction power loss occurring in the diode in the conventional switch diode circuits to the smallest value they must work at voltage above 1V. Even if the synchronous rectification is carried out with a MOSFET switch, then too it must be kept in mind that the current value should be minimum and the voltage should have a sufficiently high voltage. To meet this requirement the size of the coil may exceed the available space or it may be difficult to fabricate. Also, if a large size of the coil is utilized then it may increase the number of turns which increases the self-inductance of the coil close to the square of the total number of turns and the induced voltage may increase proportionately. To counteract this, if more conductor material is added to the coil or more turns with the same area of cross section or same turns at greater area of cross section will increase the area over which the flux will be supported in the air gap between the two magnetic materials resulting in greater volume of permanent magnet.

The voltage induced in the generator is

$$V_g = NBI_a\omega Z_1$$

Where I_a = active length of coil (length cutting the magnetic field during vibration)

N = number of turns

B = maximum flux density (approx. 1.2 tesla)

For a VDRG micro engineered generator the active length can be taken as 20mm. This will give an induced voltage per turn to be 48mV. Hence, if a single turn is used then the power that may be extracted will be around 48mV and the impedance of the turn will be very low. Now, if six turns are used instead then too the voltage will be about 300mV, which is very low for the conventional diode rectifiers. The voltage will have to be stepped up by 10 times for use in standard electronics.

The literature indicates that often such high voltages are quite difficult to achieve even if the flux gradient, active length and operating frequency are lower. Hence, low voltage rectification and stepping up of the voltage are the basic requirements of inertial micro-generator systems. The proposed converter topology has been developed to extract energy from electromagnetic micro-generator systems.

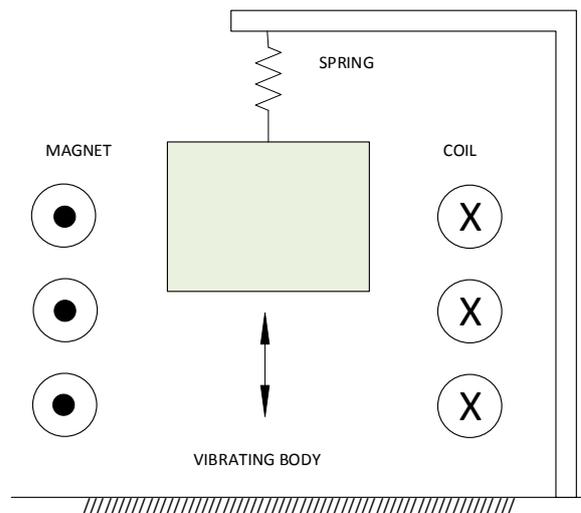


Fig 2 Schematic diagram of electromagnetic micro-generator

III. PROPOSED DIRECT LOW VOLTAGE BRIDGELESS AC DC CONVERTER

A direct AC DC converter is proposed, as shown in Fig. 3, for efficient energy harvesting from the low voltage micro generator output to voltage that can be fed to the electronic load. This converter avoids the use of bridge rectifiers, and directly converts the AC input to the required DC output. The converter utilizes a boost converter and a buck-boost converter that are operating in parallel with each other to process the positive and the negative half cycles of the AC input voltage. the micro-generator output voltage is modelled in the proposed converter as an AC voltage source. The proposed circuit consisting of various elements such as inductors, MOSFET's that constitute the switches, diodes and capacitors etc. The output is

modelled by placing a resistive load at the output terminal. There are some key points in the working of the converter. The switches S1 and S2 are realized using MOSFET's. The MOSFET's are so chosen that the forward voltage drop of their body diode is higher in value than the peak voltage of the input AC source, so that the reverse voltage applied to the switches is blocked. The diodes D1 and D2 are schottky in nature to take advantage of their very low forward voltages. The converter is designed to be implemented in the discontinuous mode of operation or DCM to reduce the switching losses and diode reverse recovery loss. The above feature also enables in the implementation of maximum energy harvesting. Also, under DCM operation, for constant duty cycle, the input current is proportional to the input voltage at every switching cycle which is beneficial for maximum energy harvesting. This study is limited to the electromagnetic micro-generators that have low output voltages (<1 V) for conversion of power. As the micro generator output is typically in a sinusoidal form, an AC voltage source whose voltage is taken in milli volts is taken. The circuit in Fig. 7 consisting of inductor L1, switch S1, diode D1 and capacitor C constitutes the boost converter, and the circuit that consists of switch S2, inductor L2, diode D2 and the capacitor constitutes the buck-boost converter to process the positive and the negative half cycles of the AC input voltage.

A. Analysis of the proposed low voltage bridgeless AC DC converter

If we plot the input current waveform of the converter together with the current waveform of the boost and buck boost converter, there are certain anomalies that will be present. Considering the input waveform of the converter, it is noted that during the positive half cycle of the input the boost inductor current (i_{L1}) and the input current i are equal, but during the buck-boost converter operation, the input current i and the buck-boost inductor current (i_{L2}) are not equal. This happens because during the buck boost converter cycle, the input current becomes zero during the period when the switch is turned OFF. Hence the energy transferred to the output by a buck-boost converter cycle is equal to the energy that is stored in the inductor, whereas, in the boost converter cycle, the energy transferred to the output exceeds the energy stored in the inductor as shown in Fig. 6. Therefore, for equal duty cycles, the input voltages and input values of the inductor are equal ($L1 = L2$). But, the total power delivered by both the converters over an input cycle of voltage are not equal. The relationship between the control and circuit parameters of the boost and the buck-boost converters pertaining to the input power and the output power is obtained in the analysis of the converter.

Considering the k th switching cycle of the boost and the buck-boost converters, where:

- T_s = time period of the switching cycle
- D_b = duty cycle of the boost converter
- $d_f T_s$ = boost inductor current fall time
- D_c = duty cycle of buck-boost converter
- v_i = input voltage of generator with amplitude V_p
- V_o = converter output voltage

The equations for the input cycle of the converter can be expressed as depicted in Fig. 4:

$$v_{ik} = V_p \sin\left(\omega t + \frac{2\pi k T_s}{T_i}\right);$$

$$m_1 = \frac{v_{ik}}{L_1}; m_2 = \frac{V_o - v_{ik}}{L_1}$$

The switching time period of the converter (T_s), is much smaller than the time period of the input AC voltage cycle, given by T_i , therefore the peak value of the inductor current i_{pk} in the boost converter cycle can be written as:

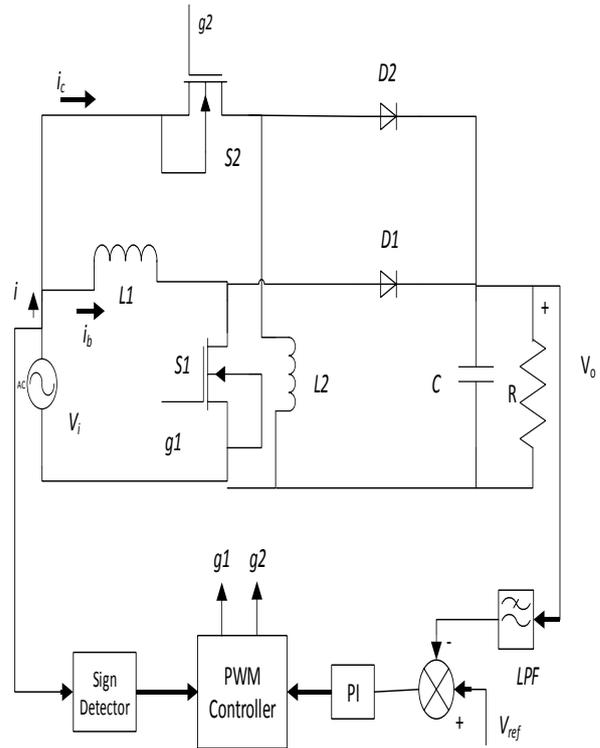


Fig 3 Proposed direct AC DC converter diagram

$$i_{pk} = m_1 D_b T_s = \frac{v_{ik} D_b T_s}{L_1}$$

The current in the inductor starts to fall when the boost converter switch is turned OFF. The slope (m_2) of this current is determined by the voltage present across the inductor. During k th switching cycle, the voltage that is present across the inductor during current fall time can be written as $V_o - v_{ik}$. The inductor current fall time can be hence, found as:

$$d_f T_s = \frac{i_{pk}}{m_2} = \frac{i_{pk} L_1}{V_o - v_{ik}}$$

During this cycle, the total amount of energy that is transferred from the input of the boost converter is derived as:

$$E_{kb} = \frac{v_{ik} i_{pk} (D_b - d_f) T_s}{2}$$

The average power that is supplied in the switching cycle of the boost converter is:

$$P_{ik} = \frac{E_k}{T_s} = \frac{v_{ik} i_{pk} (D_b - d_f)}{2}$$

During the time duration or time period of one switching cycle, the number of switching cycles are defined as $N = T_i/T_s$. Since the boost converter is operated for half time period of the AC cycle given by $T_i/2$, the average input power of the boost converter during this half time period is given as:

$$P_{ib} = \frac{2}{N} \sum_{k=1}^{N/2} P_{kb} = \frac{2}{N} \sum_{k=1}^{N/2} \frac{v_{ik} i_{pk} (D_b - d_f)}{2}$$

For large values of N , discrete function is treated as a continuous function. Therefore, the average input power of the boost converter can be obtained if we integrate the term in the summation over the half cycle period of the input AC voltage. The mean value can be taken then. Hence, on the form of integration the boost converter power of the positive half cycle can be expressed as:

$$P_{ib} = \frac{2}{T_i} \int_0^{T_i/2} \left(D_b T_s V_p^2 \sin^2 \left(\frac{2\pi t}{T_i} \right) \right) * V_o \left(V_o - V_p \sin \left(\frac{2\pi t}{T_i} \right) \right)^{-1} dt$$

$$v_i = \text{micro-generator input voltage} = V_p \sin \left(\frac{2\pi t}{T_i} \right)$$

After solving the above equation, the power for the boost converter P_{ib} is found as:

$$P_{ib} = \frac{V_p^2 D_b^2 T_s \beta}{4L_1}$$

$$\text{Where } \beta = \frac{2}{\pi} \int_0^{\pi} \frac{1}{1 - \frac{V_p}{V_o} \sin \theta} d\theta \text{ and } \Theta = \frac{2\pi}{T_i}$$

It is duly noted from the above equations and analysis that the value of β is constant for the fixed value of V_p and V_o . for larger values of switching frequency of the converter, the average power is independent of the micro-generator output frequency and the output voltage. During the steady state operation, the average input power of the converter is equal to the summation of the average output power and the various losses of the converter. Hence, by defining the efficiency of the converter as η , for a load resistance R , the power of the input and output can be balanced as:

$$\frac{V_p^2 D_b^2 T_s}{4L_1} \beta = \frac{V_o^2}{R\eta}$$

The boost converter duty cycle D_b can be thus obtained as:

$$D_b = \frac{2V_o}{V_p} \sqrt{\frac{L_1}{R\eta\beta T_s}}$$

Now, considering the operation of the buck-boost converter, the input power is supplied only during the ON period of the switch S_2 . During the OFF cycle of the switch S_2 , the input current is zero, therefore for any k th switching cycle, the average power that is being supplied by the buck-boost converter can be obtained by evaluation as:

$$P_{kc} = \frac{v_{ik} i_{pk} D_c}{2}$$

The average power can be expressed in the buck-boost converter in the same way as in the boost converter. The integration form of the average power is given by:

$$P_{ic} = \frac{2}{T_i} \int_0^{T_i/2} \frac{D_b^2 T_s}{2L_1} V_p^2 \sin^2 \left(\frac{2\pi t}{T_i} \right) dt = \frac{V_p^2 D_b^2 T_s}{4L_1}$$

The duty cycle for the buck boost converter can be obtained as:

$$D_c = \frac{2V_o}{V_p} \sqrt{\frac{L_2}{R\eta T_s}}$$

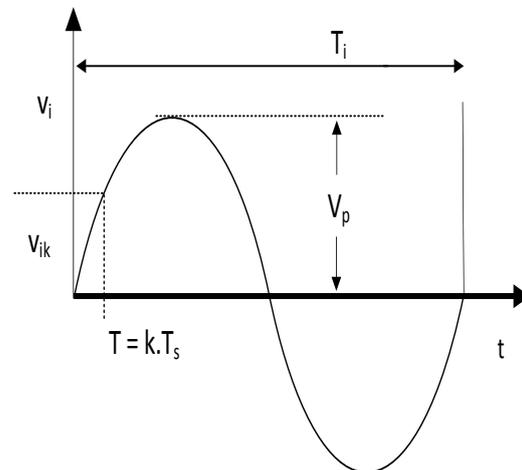


Fig 4 Input voltage during the switching cycle of the converter

The duty cycle of the boost and buck-boost converter can be related as:

$$\frac{D_b}{D_c} = \sqrt{\frac{L_1}{\beta L_2}}$$

Where D_b = duty cycle of boost converter

D_c = duty cycle of buck-boost converter

Based on the above equation there can be two different control methods that can be proposed for the converter so that it delivers equal average input power. The first method can be to keep the values of the inductors equal, i.e. $L_1 = L_2$, and the control of the converters are carried out with different duty cycles. In this case the condition $D_c = D_b \sqrt{\beta}$ is satisfied and the converter operates with different duty cycles. The second method both the converters, boost and buck-boost are controlled with the same duty cycle ($D_b = D_c$) and therefore the inductor values relate as: $L_1 = \beta L_2$. The variable β is being plotted as a function of step ratio i.e. V_o/V_p in the Fig. 5. It can be deduced that for greater values of voltage step up ratio, the value of β approaches unity.

Therefore a very important conclusion is thereby presented, that if the step up ratio is very high, then the value of β will tend to unity and the converter can be designed with parameters with equal duty ratio and equal value of inductance. This result is very useful for the proposed converter because very low voltage is stepped up to a comparatively higher amount of output voltage.

IV. SIMULATION OF THE PROPOSED LOW VOLTAGE BRIDGELESS AC DC ENERGY CONVERTER

An electromagnetic micro-generator based on the resonating influence, producing a peak sinusoidal output voltage of 400mV having 100Hz frequency is considered

in this study for the proposed converter topology. The closed loop simulation is carried out based on the control schemes discussed previously. The reference output voltage (V_{ref}) is taken to be 3.3 V. the energy harvesting converter is simulated to supply power to a 200Ω resistor, therefore, supplying a 55mW of output power.

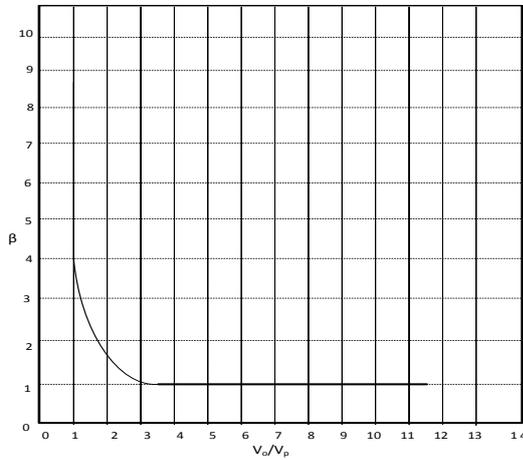


Fig 5 Plot of β versus V_o/V_p

Based on the previous analysis and design guidelines discussed the converter design is carried out. MOSFETs are used for the realization of the switches S_1 and S_2 . The forward voltage of the selected MOSFET body diode is about 0.8V, which is taken to be higher than the peak voltage at the input. This inhibits any reverse current flowing in MOSFETs. The nominal duty cycle is assumed to be 0.7. The inductor is designed for a standard value of 4.7μH and is commercially available. Based on these design values, the frequency of switching can be approximated as 50kHz. The diodes, D_1 and D_2 are chosen to be the schottky type and have a low value of forward voltage. The output capacitor value is 68μF. The simulations of the converter are carried out in mathworks software. Circuit models of the selected devices and components, are used in the simulations. The various values for the circuit components of the proposed converter have been already discussed. In the simulation, the duty cycle of the boost converter D_b is estimated by a PI controller. The buck-boost converter duty cycle D_c is calculated from the duty cycle estimated D_b . the input current of the boost and the buck-boost converter for load $R=200\Omega$. The total input current and the micro-generator output voltage will be shown by the simulation results. The boost converter is operated during the positive half cycle, and the buck-boost converter is operated during the negative half cycle of the micro-generator output voltage. The results are obtained in MATLAB simulink software. The output ripple is 0.14% V, which is approximately 4.24% of the nominal output voltage. The efficiency of the converter is approximated to be 63%. The duty cycle from the analysis is calculated to be equal to 0.71. The estimated duty cycle of the converter closely matches the estimated duty cycle that was calculated analytically. The output to input peak voltage ratio is $V_o/V_p = 8.25$. Furthermore, the duty ratios of both the boost converter and the buckboost converter are found to be almost equal hence, the previous conclusions are

corroborated that for higher step-up ratios the duty ratios and the inductance values for both the converters are almost equal. For a simple control structure, and less complicated circuitry, both the boost and the buck-boost converters can be controlled with same duty ratios if the voltage are high. To validate the speculations, simulations are carried out and from the resulting plots it is seen that the converter is able to produce successful results with desired output voltage and ripple. The output from the micro-generators is modelled by the AC voltage source in the converter circuit and the waveforms obtained are shown below in Fig. 8. The waveforms through the inductor current of the boost and the buck-boost circuit are shown in the diagram below. It is clearly depicted that during the positive half cycle of the converter current flows through the boost circuit and during the negative half cycle it flows through the buck-boost circuit. The waveform in Fig. 9 explicitly describes the process. The output of the converter is a stepped up DC wave of 3.3 V in magnitude. This output is sufficient to feed small scale power electronic devices.

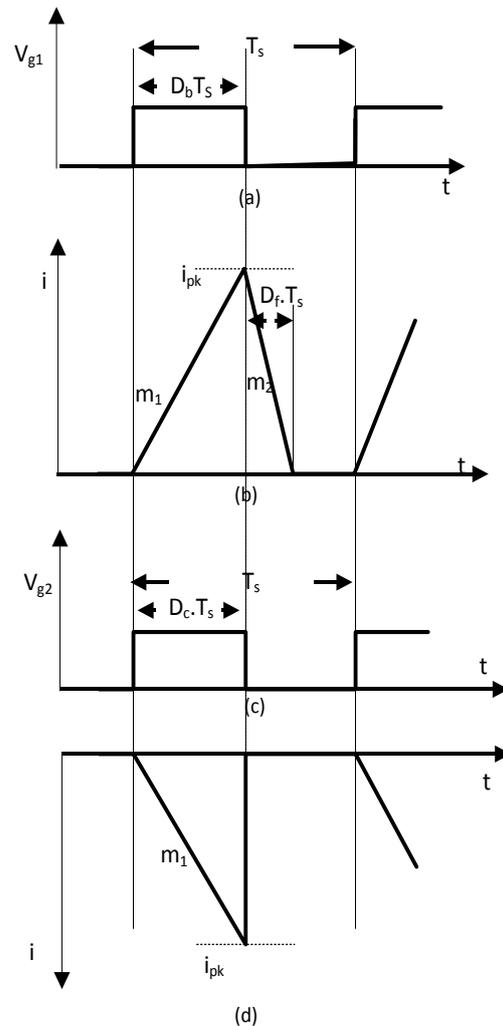


Fig 6 (a) gate signals during the boost cycle (b) Input currents during a switching cycle of boost converter waveform of the converter (c) gate signals during the buck-boost converter cycle of the converter (d) input current during the buck-boost converter cycle

The results obtained from the simulation of the proposed converter are hence verified by the load $R = 200 \Omega$. The output waveforms are shown in Fig. 10.

V. CONCLUSION

The electromagnetic micro-generators that form the basis of the low voltage energy harvesting technique have been analysed. A direct method for the low voltage bridgeless AC DC energy conversion has been proposed by paralleling a boost converter with a buck-boost converter. The positive and negative half cycles of the micro-generator output voltage are processed by the boost and the buck-boost converter respectively. The negative gain present in the buck-boost converter has been used to step up the negative half voltage cycle of the converter to a positive DC voltage.

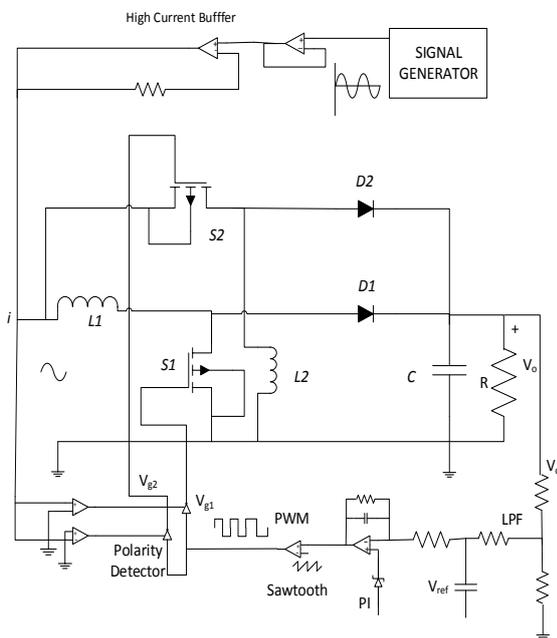


Fig 7 Circuit diagram of energy harvesting converter

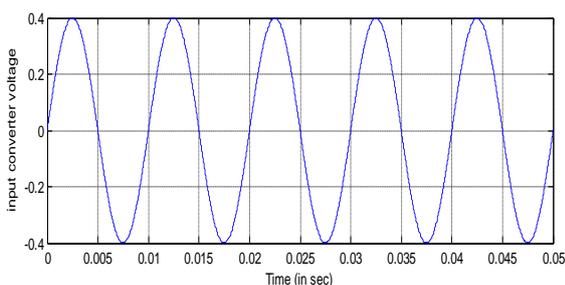
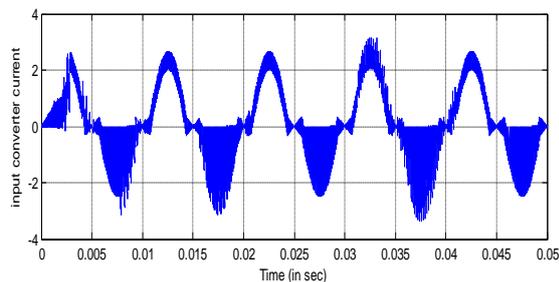


Fig 8 Input current and voltage waveforms for simulation of circuit with feedback

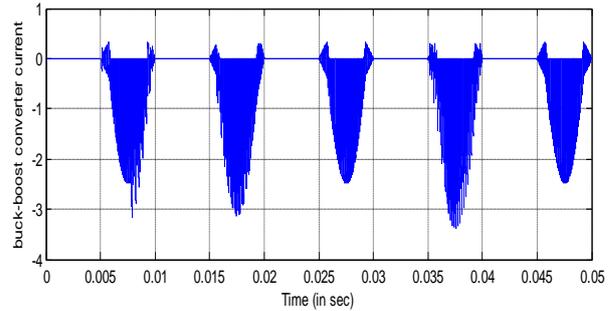
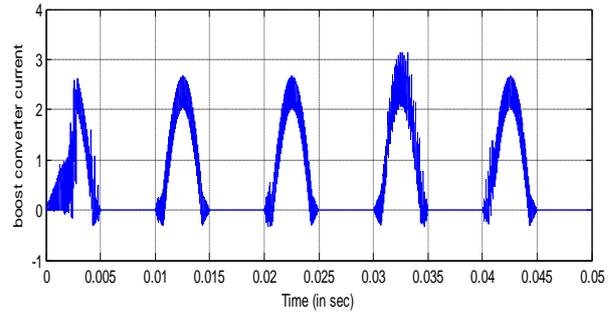


Fig 9 Boost and buck-boost converter currents

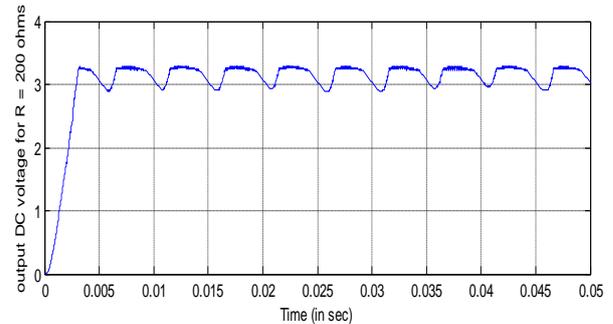
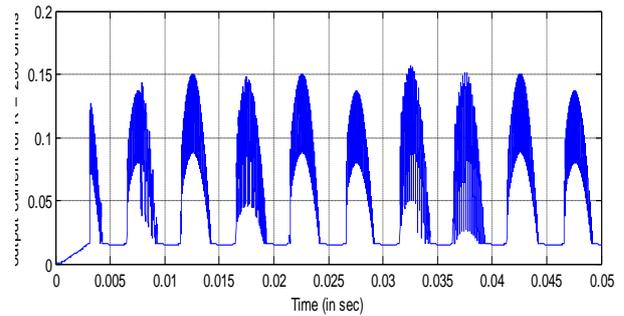


Fig 10 Output current and voltage waveforms for $R = 200\Omega$

Analysis of the micro-generator and the proposed converter has been carried out to obtain the desirable results. Based on the above, a prototype of the converter has been demonstrated in the MATLAB Simulink software. The efficiency of the converter simulated has been found to be 63%, the voltage ripple about 5% of the nominal voltage and the power consumption around 55mW. The converter has been successfully operated to step up the low power voltage in milli volts fed from the AC micro-generator to higher DC voltage to be fed to an electronic load. The loss components have been calculated and presented. The output to input ratio of the converter,

Vo/Vp was found to be equal to 8.25. Hence, the proposed converter has been successfully implemented.

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