SEBHA UNIVERSITY JOURNAL OF PURE & APPLIED SCIENCES VOL.22 NO. 1 2023
DOI: 10.51984/JOPAS.V22I1.2339

مجلة جامعة سبها للعلوم البحتة والتطبيقية
Sebha University Journal of Pure & Applied Sciences

Journal homepage: www.sebhau.edu.ly/journal/index.php/jopas

A bridgeless AC-DC step up regulator circuit for piezoelectric energy harvester

*Adel Issa Ben Issa, Salem Alarabi Shufat, Jamal Mohamed Ahmed, Hasan Abunouara

Electric and Electronic Engineering Department, Higher Institute of Engineering Technology, Tripoli, Libya

Keywords:
AC-DC Converter
boost converter
buck convert
Piezoelectric
Simulation

ABSTRACT

Various applications of the piezoelectric energy in the modern world require an efficient AC-DC low power converter. As the two stages converter with bridge rectifiers may not be used because the diodes would not be suitable for low volt ranging between 100 to 200mv, these are considered an efficient element in the low volt circuits because of their entire losses. In this paper, a small and efficient AC-DC low power converter is presented. It directly converts low AC voltage to the required output DC voltage using one stage instead of bridge rectification. The proposed converter combines both boost and buck boost converters which are parallel constructed to condition the positive and negative half cycle of the input AC volt respectively. Two inductors and one capacitor are used for booth circuits in terms of reducing the size. The circuit is tested at 50 kHz switching frequency with two different duty cycles to rectify a 0.5 AC volt to about 3 DC volts with an estimated efficiency of 65%. The simulation result was 3.7 DC V from 0.5 ACV. The circuit analysis and the design guide line are explained. The circuit is designed and tested using Matlab (Simulink) software.

دائرة منظم AC-DC رافع بدون قنطرة للطاقة الكهروضغطية

*عادل عيسى بن عيسى و سالم العربي شفاط و جمال محمد أحمد و حسن أبونوارة

قسم التقنيات الكهربائية والإلكترونية، المعهد العالي للتقنيات الهندسية ، طرابلس، ليبيا

الكلمات المفتاحية:
محول باك
الكهرضغطية
محول AC-DC
محاكاة
محول رفع

الملخص

تتطلب التطبيقات المختلفة للطاقة الكهروضغطية في العالم الحديث محول طاقة منخفض AC-DC فعال نظرًا لأن المحول ذي المرحلتين مع مقومات القنطرة قد لا يتم استخدامه لأن الثنائيات لن تكون مناسبة للجهد المنخفض الذي يتراوح بين 100 إلى 200 mv ، فهذه تعتبر عنصرًا فعالًا في دوائر الجهد المنخفض بسبب خسائرها بالكامل. في هذا البحث يتم تقديم محول طاقة منخفضة AC-DC صغير وفعال، حيث يقوم بتحويل جهد التيار المتردد المنخفض مباشرة إلى جهد الإخراج (DC) المطلوب باستخدام مرحلة واحدة بدلاً من تصحيح القنطرة. يجمع المحول المقترح بين كل من محولات التعزيز والتعزيز باك (Buck) التي يتم إنشاؤها بشكل متوازي لتكييف نصفي الموجة الموجب والسالب لمدخل التيار المتردد على التوالي. يتم استخدام ملفين حثيين ومكثف واحد لكلا الدائرتين لتقليل الحجم. يتم اختبار الدائرة بتردد 50 كيلو هرتز مع دورتي عمل مختلفتين لتقويم الجهد المتردد 0.5 فولت إلى حوالي 3 فولت تيار مستمر بكفاءة تقديرية تبلغ 65٪. كانت نتيجة المحاكاة 3.7 جهد مستمر من 0.5 جهد متردد. تم شرح وتحليل الدائرة وكذلك خطوات التصميم، حيث تم تصميم واختبار الدائرة باستخدام برنامج (Simulink) Matlab.

Introduction

The power requirements for electronic devices have been reduced dramatically over the last decades because of the development of energy efficient semiconductor devices. Batteries to supply the electronic loads may not be used because of the short time of their running life; hence, batteries are replaced by self-powered devices which can perform continuous operations without external power supply due to harvesting the ambient energy. This development has led to the increase and development of wireless electronic devices, medical implant, power sensors and other low power electronic devices which require a low voltage ranging between hundreds of mv. The self-power is due to harvest the environment energy in the form of heat light and vibration [1]. Low frequency vibration, human

*Corresponding author:
E-mail addresses: adelissa1976@gmail.com, (S. A. Shufat) s.shffat@hiett.edu.ly, (J. M. Ahmed) J.ashish@hiett.edy.ly, (H. Abunouara) H.abonouara@hiett.edu.ly

Article History : Received 09 December 2022 - Received in revised form 07 February 2023 - Accepted 12 February 2023

motion, noise and solar are considered as some sources that can be exploited by the harvester energy system. The mechanism for harvesting these types of energy is piezoelectric, electrostatic and electromagnetic. The piezoelectric micro generator harvests the energy by converting the mechanical strain to electric current while the electrostatic harvests the energy using the phenomenon of charging the vibration capacitance. Moreover, the electromagnetic harvest the energy by converting the vibration to electric energy using a magnetic inductor. The output of the piezoelectric and electromagnetic is an AC while the electrostatic generates DC volt. [2]
The piezoelectricity as shown in figure (1) is one of the topics which continue to be something for laboratory research for the next decades as many works have been done to define and explore the crystal as element which exhibits piezoelectric. Micro power generator of the piezoelectric is an element which produces an electrical potential with low current and high volt. This production of the potential is caused when the piezoelectric material is put under strain of either compression or deflection. This material is either traditional type such as crystal or micro fibre composites (MFC) [1]. For example, piezoelectric desk can generate electricity when changing in shape is occurred due to compression or deflection.

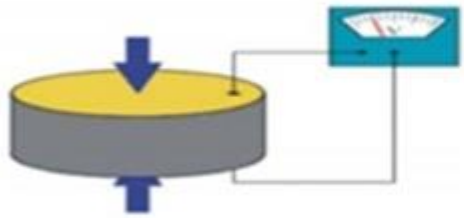


Fig. 1: Diagram of piezoelectric [1]

The main advantages of piezoelectric element are:
- No need for external energy source.
- The energy density is high compared to the other components.
- Produce voltage ranging between 2-10V.

In comparison to the electromagnetic and electrostatic, the piezoelectric has the highest energy density [1].
Piezoelectric micro generators are generating an AC volt, however the operation of the electrical devices requires DC volt. Hence, the output of piezoelectric electric micro generators needs to be processed using a suitable low power converter to fulfil the required DC volt for the load [3].
Since size and efficiency are the main factors for designing electronic devices, this paper has avoided using bridge rectification which uses diodes for rectification and DC-DC converter in the second stage and replaced it by one stage only for rectifying and boosting the low input volt. The output is passed to one capacitor which charges both cycles of the micro generator output. However, extremely large capacitor is needed to reduce the ripple at the output DC bus.
A new direct AC - DC converter for low power applications is proposed in order to rectify low AC volt (0.5v) and boost it to about (3.17 DC v) which is the required voltage for many different electronic devices. This converter consists of boost converter in parallel with buck boost converter. When the low power input source is positive the boost converter is working. Similarly, buck boost converter only works when the input volt is in the negative half cycle.
The main objective of this paper is to design and simulate an efficient AC-DC converter which can be used in the low volt applications such as harvesting the vibration energy, kinetic energy or solar energy circuits. Additionally, the proposed converter helps to avoid using the rectification bridge which will be an opportunity to improve efficiency. Moreover, the proposed model helps to rectify very low Ac voltage ranging between 400-500mv and boost it to about 3.17Dc volt at about 200 microwatts.

Bridgeless AC-DC converters
Another method of maximizing the efficiency of the AC-DC converter is by using bridgeless AC-DC converter. Thus, in order to condition the positive and negative of the input AC volt, either split capacitor and bidirectional switch or two parallel DC-DC converters are used in these topologies. Fig (2) shows the split capacitors topologies. Because of the low operation frequency of the harvesting micro generators, the capacitor needs to be large enough to suppress the ripple voltage in the desired level. Increasing the storage components in these converters lead to an increase in the size which will make these topologies impractical due to the size limitation of the energy harvester. By contrast, two synchronous MOSFETs could be used to eliminate the split capacitor. However, increasing the switches would incur extra switch losses in the circuit [4].

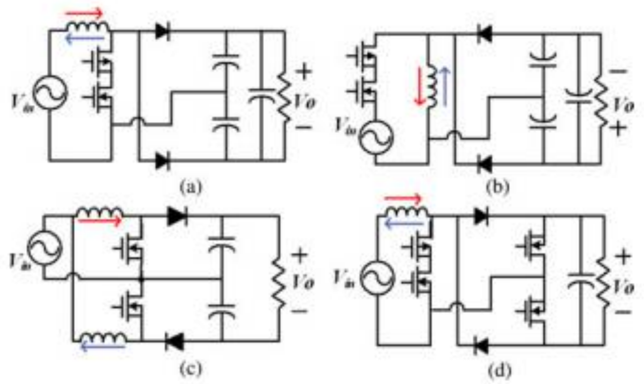


Fig. 2: Slit capacitor topology (a) split capacitor boost converter. (b) Split capacitor buck boost converter. (c) Two switch boost converters. (d) Boost converter with secondary switch. [4]

Due to high efficiency, voltage step capability and simple structure boost converter is the common power conditioning interface. Thus buck boost converters are capable to convert the negative input volt. The boost and buck boost converter could share the same capacitor to meet the required weight and size.
An efficient bridgeless boost converter is shown in figure (3). The proposed converter consists of boost and buck boost converter technique. This topology is introduced for piezoelectric harvester application.

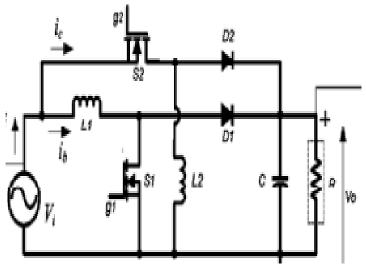


Fig. 3: Proposed direct AC-DC converter for low volt application [5]

Principle of operation:
The typical output voltage from piezoelectric generators is sinusoidal. In this circuit the design of the piezoelectric generator is modelled as a sinusoidal AC voltage source. As the proposed converter is for low volt application is assumed to supply few hundred mill volts.
The proposed converter is shown in Figure (3). It consists of boost converter which is parallel connected with buck boost converter. Boost converter consists of (S1, D1, L1); whereas (S2, D2, L2) are for the buck boost converter. The output capacitor (C) which is connected in parallel with the load (R) is charged by the boost converter in the positive half cycle and by the buck boost converter in the negative half cycle of the input AC volt. Switches (S1, S2) are N channel MOSFETs are used to reverse the voltage by the AC output of the micro generators. The forward volt (fv) of the body diodes of the MOSFETs should be higher than the peak voltage of the input source. D1 and D2 are chosen to be Scotty diodes with low forward voltage in order to reduce the losses caused by the diodes. As the input voltage source is assumed to have low frequency of about 100Hz, the switching frequency for both switches need to be higher than the input frequency. This topology is operated under discontinues mode (DCM). Using (DCM) mode reduces the turn ON-OFF losses of the switches. In

addition to that, diode reverse recovery losses are reduced. Additionally, using this mode makes the implementation of the control scheme simple in this converter.
The Discontinues mode (DCM) of the proposed topology is illustrated in the following figures below. There are four different modes for each cycle of the input voltage. 1 and2 modes describe the operation of the circuit in the positive half cycle of the input AC volt. In these modes (S1) is turned ON where (D1) is reverse biased. The converter operates as boost converter in these modes, where (3, 4) modes shows the operation of the converter in the negative half cycle of the input voltage. In these modes the converter is working as buck boost converter by switching S2 ON and D2 is automatically reversed.

Mode (1):
This mode starts only when switch (S1) is turned ON at zero time (t_0) as shown in Figure (4). To reduce the losses of switching (S2) ON zero current switches (ZCS) needs to be used. The inductor (L1) is energized by means of S1and the current rise from zero. Both of the diodes are in the reverse biases condition. In this mode the load is supplied by the energy stored in the output filter capacitor (C).

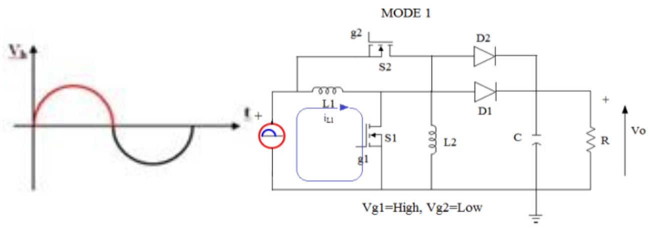


Fig. 4: Mode 1 of the proposed converter [6]

Mode (2):
Mode (2) as shown in figure (5), begins when S1 is turned OFF at specific period of time (t1) and (t_1-t_0= d_iT_s). Where (di)is the duty cycle and (T_s) is the period of switching. The energy stored in the Inductor (L_1) in the mode (1) is passed to the load during D1, also the inductor current decreases linearly while transferring the energy to the load. When the inductor current reaches to zero at (t_2) D2 is turned off automatically to avoid the reverse recovery losses. As in mode (1) the load is supplied by the energy stored in the capacitor (C). If the input AC volt is still positive the converter will go mode (1) as soon as S1 is in the ON condition.

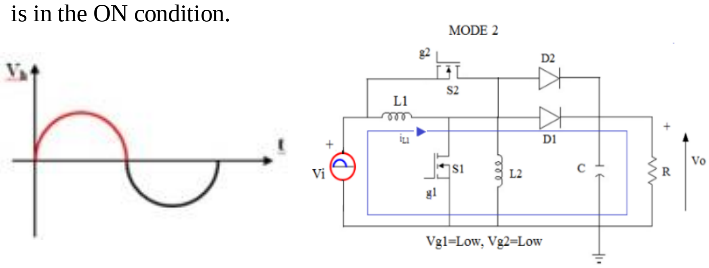


Fig. 5: Mode 2 of the proposed converter [6]

Mode (3):
As soon as the input voltage is negative this mode begins when S2 is turned ON at (t_0\`). By ensuring the converter to operate in (DCM) the (ZCS) condition can be achieved as in Mode (1). The inductor (L2) still builds where the load is powered by the output capacitor as in figure (6).

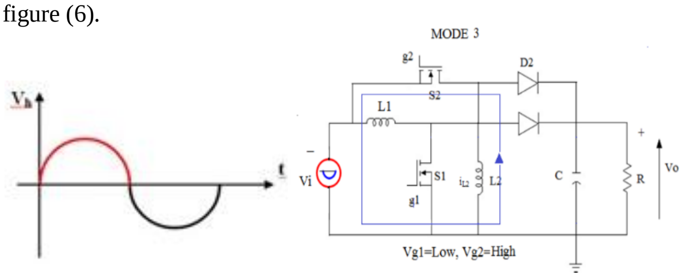


Fig. 6: Mode 3 of the proposed converter [6]

Mode (4):
When S2 is turned off after a specific time represented by (t_1\`), this mode starts as shown in figure (7) where ($t_1$\`-t_0\`= di\`Ts , d1\` is the duty cycle of the buck boost converter. The stored energy in the inductor from the previous mode is transferred within the (D2) to the filter capacitor (C) which feeds the load. The inductor current will have the same characteristics as in mode (1) that will decrease linearly. By switching (D2) ON switching losses occurs in this mode. As soon as the inductor current becomes zero at (t_2\`($t_2$\`-t1\`=d2\`Ts) automatically D2 will be in the OFF condition at zero current. The output capacitor powers the load by the stored energy. If the input voltage is still in the negative half cycle, the converter will return to mode (3) when S2 is switched ON.
Referring to the four different operation modes of the converter, the switches are operating in DCM which is more efficient than the continuous mode.

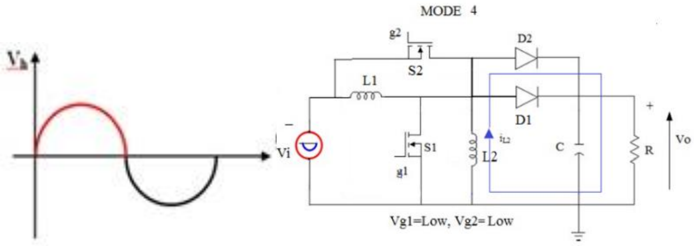
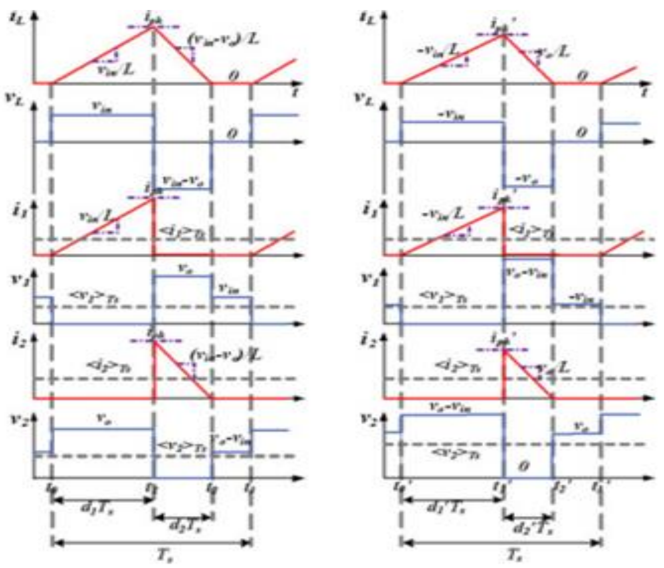
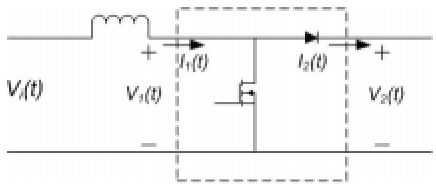


Fig. 7: Mode 4 of the proposed converter [6]

1. Theoretical analysis of the proposed converter.
Several assumptions have been made for switching cycle in order to get simple analysis of the proposed topology of the converter as shown in figure (8).[7,8,9]



(a)



(b)

Fig. 8: (a) Boost waves (b) Buck boost operation modes [7]

The assumptions are:
1) The input source assumed to be sinusoidal voltage source.
2) The switching frequency of the two MOSFETs needs to be much higher than the frequency of the input source.

3) For each switching cycle, the input voltage could be assumed as a constant voltage source. It can be represented by: [7,8,9]

$$v_{in}(\mathrm{t}) = V_m \sin\left(\frac{2\pi t}{\mathrm{Ti}}\right), \quad (1)$$

Where: T_i is the time period of input source.

The output capacitor (C) assumed to be large enough to keep the output voltage constant.

4) For proper calculation, the internal series resistance of the passive components would not be accounted for.

5) During the boost operation cycle (t_0,t_3) as in Figure (8) the average value of the MOSFET can be expressed by the following equation.

$$v_i(t) = (1 - \mathrm{d1} - d_2)(v_{in}(\mathrm{t})T_s + d_2(v_0(\mathrm{t})T_s) \quad (2)$$

In Figure (8.a) by integrating the ii (t) waveform in one cycle the average switch current will be:

$$i_1(t)T_s \int_{t0}^{t3} t_1(t)\,dt \quad (3)$$

The average diode current (ι2(t)Ts and the average diode voltage(υ2(t)Ts are respectively expressed as:

$$i_1(t)T_s = \frac{1}{T_s}\int_{t_0}^{t_3} i_2(t)\,dt = \frac{d2^2Ts((vo(t))-(vin(t))}{2l} \quad (4)$$

$$v_2(\mathrm{t})T_s = (\upsilon\mathrm{o}\ (\mathrm{t})\mathrm{Ts}\ d_1 + (1 - d_1 - d_2)(v_0(\mathrm{t})T_s - v_{in}(\mathrm{t})T_s) \quad (5)$$

Inductor volt second balance d_2(t) is related to d_1 (t)

$$d_2(t) = \frac{(\mathrm{vin(t)})}{(\mathrm{vo(t)})-(\mathrm{vin(t)})} \quad (6)$$

From the equations (2), (6)

$$\frac{(v_1(t))\ T_s}{z(i_1(t))\ T_s} = \frac{2L}{d_1^{\ 2}\ T_s} \quad (7)$$

$$((v_2(t)T_s - i_2(t)T_s) = \frac{(v_i(t))\ Ts}{Re} \quad (8)$$

Note:

For the buck boost converter analysis, the same equations can be applied to find the average voltage and current during one cycle (t₀`, t₃`)

From the equation (7) it can be noted that the average voltage (υ2(t)Ts) is proportional to the average current ($i_1(t)T_s$). In other words:

$$R_e(d_1) = \frac{2L}{d_1^{\ 2}\ T_s} \quad (9)$$

Using (8) and (9) the diode output power can be represented by:

$$P(t)T_s = v_2(t)T_s\ (i_2(t)T_s) \quad (10)$$

In the steady state the equivalent circuit of the proposed converter topology can be modelled by placing the average model instead of the switch network, also the inductor can be replaced by short circuit and the capacitor by an open circuit as indicated below in Figure (9).

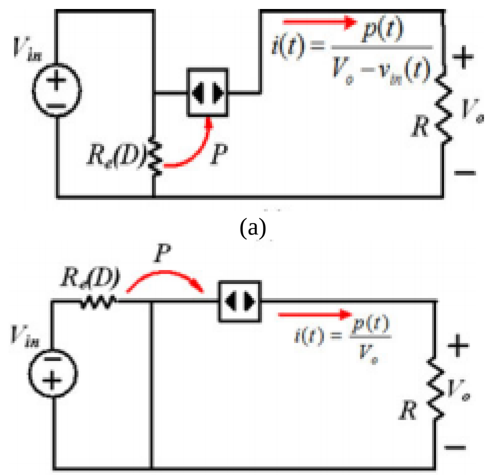


Fig. 9: Equivalent circuits: (a) Boost converter (b) Buck boost converter.

The delivered power in boost operation in Figure (9.a) can be written as:

$$P(t) = \frac{v_{in}^{\ 2}(\mathrm{t})}{R_e} = \frac{v_{in}^{\ 2} sin^2(2\pi/T_i)}{R_e} \quad (11)$$

The current flowing through the load (R) can be expressed as:

$$i(t) = \frac{p(t)}{v_o - v_{in}(t)} = \frac{v_m^{\ 2}\sin^2(2\pi/\mathrm{Ti})}{R_e - [vo - Vm\sin(2\pi/\mathrm{Ti})]} \quad (12)$$

$$\mathrm{E_{in}} = \int_0^{Ti/2} P_L(\mathrm{t})\mathrm{dt} = \int_0^{Ti/2} \frac{v_m^{\ 2}\sin^2(2\pi/\mathrm{Ti})}{R_e - [vo - Vm\sin(2\pi/\mathrm{Ti})]} \quad (13)$$

The consumed energy can be expressed as:

$$E_0 = \int_0^{Ti/2} p_0(\mathrm{t})\mathrm{dt} = \int_0^{Ti/2} \frac{v_0^{\ 2}\ \mathrm{Ti}}{2R} \quad (14)$$

The input voltage for energy harvester is usually less than 500mv, however the majority of the electronic loads are driven by about 3v or more.

From the previous equations it can be reordered to give:

$$\frac{v_0^{\ 2}\ \mathrm{Ti}}{2R} = \frac{v_m^{\ 2} d_1^{\ 2}\ T_i T_s}{8L} \quad (15)$$

Simulink results:

In this part the pulse signal for the MOSFETs is generated by using pulse generator as in figure (10), consists of the following components:

- **AC voltage supply-** This supply is generating low volt AC (0.5v at 100Hz) which represents the micro generator harvested energy.
- **MOSFETs-**Two N channel MOSFETs are used as a switch in this topology for boost and buck boost converter respectively. The forward volt of the entire body diode is very low; similarly, the MOSFET entire resistance is sited to be very low as the input is in mill volts.
- **Diodes-**Tow diodes are used for boost and buck boost converter. The forward voltage of the two diodes tends to be very low.
- **Inductor-**Two inductors are used for both converters as explained before. From the analysis equations and charts the inductor value is selected to be (4.7µH).
- **Capacitor-** Single capacitor has been used at the output in order to filter the output and feeding the load resistance. The value of the capacitor is selected to be (68µF).
- **Load resistance - (**200 Ω) resistance has been used in this topology as an electrical load.
- **Switching frequency:** A pulse generator tool has been used to generate the required pulse for the two MOSFETs. As the inductor value is given the switching frequency is calculated to be (50 KHz).

Hence:

F= 1/T so the duty cycle T 1/50,000= 20µs.The pulse width is 25% which means that the MOSFET is ON for (0.5µs). The second pulse for the second MOSFET will have the same width and will be delayed by (10µs) as shown below. Also 50% pulse width will be used in order to evaluate the changes in the output volt.

Converter circuit

Figure (10) shows the complete circuit of the converter in Simulink software. This circuit is going to rectify and boost input AC voltage which equals to (0.5VAC) to about 3.7VDC as in Figures (11,12). The setting for the circuit parameters will be shown below.

The width of the switching pulses (1,2) will be 50% as a first test (Figure (13)), and because of increasing the losses due to increases the pulse width, the 25% pulse width will be used as a final test (Figure (14)).

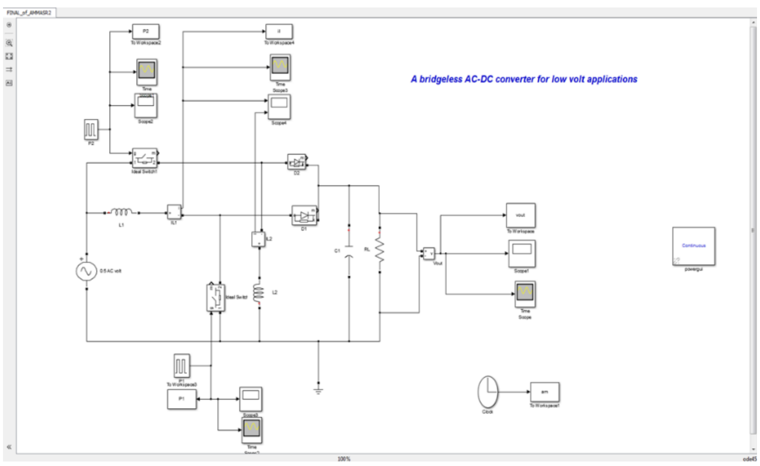


Fig 10. Input AC volt (0.5ACV) rectified and boosted to 3.7 DC volt.

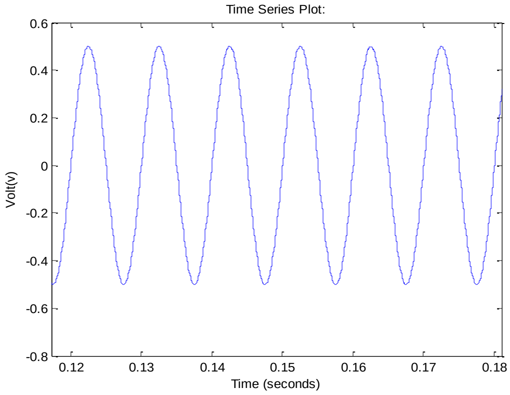


Fig 11: input AC volt (0.5 @100Hz)

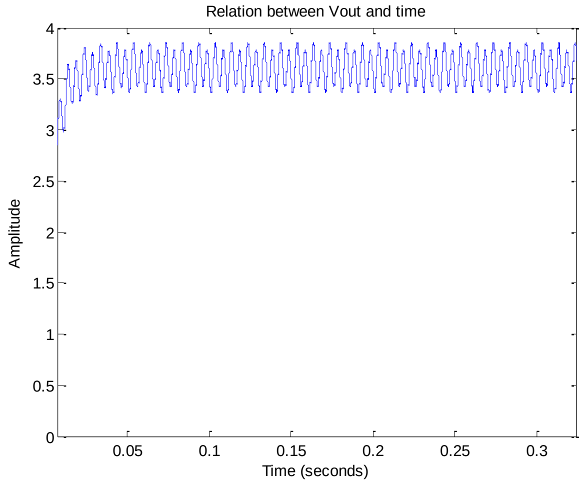
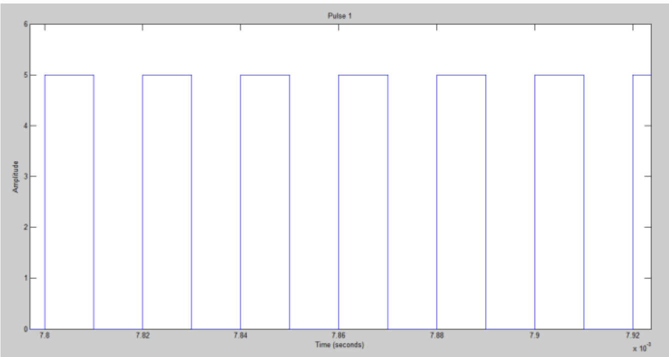
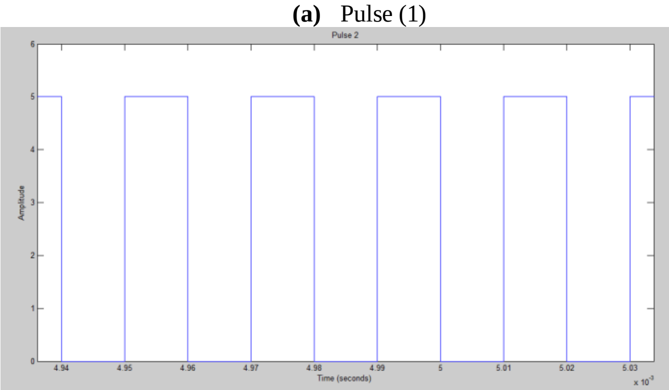


Fig 12: Output dc volt which is about 3.7v



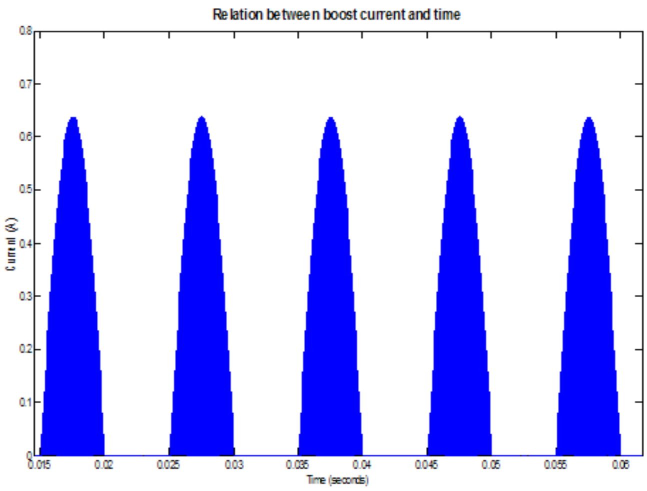
(a) Pulse (1)



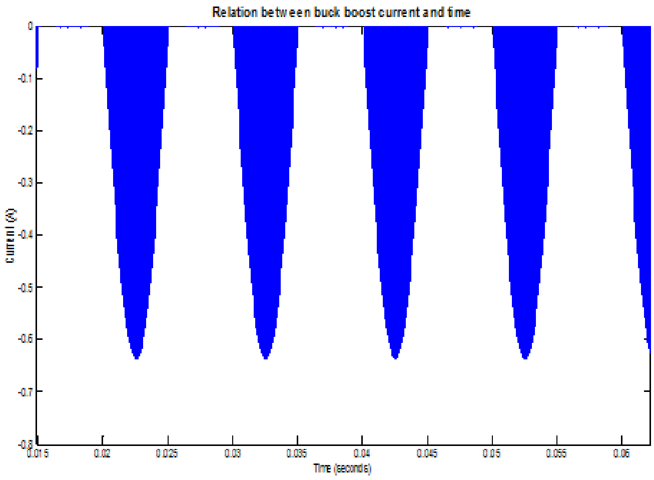
(b) Pulse (2)

Fig 13: Switching pulses with 50% width

Figure (14) shows the characteristics of the inductor current of boost and buck boost converters. The inductor energizing up to (0.7A) then start charging the capacitor in boost converter. Similarly, buck boost inductor energized up to (-0.7A) then the capacitor star charging



(a)



(b)

Fig 14: Inductor current inductor value for both: (a) boost and (b) buck boost

Figure (15) shows the output volt and inductor current in relation to time in the same graph.

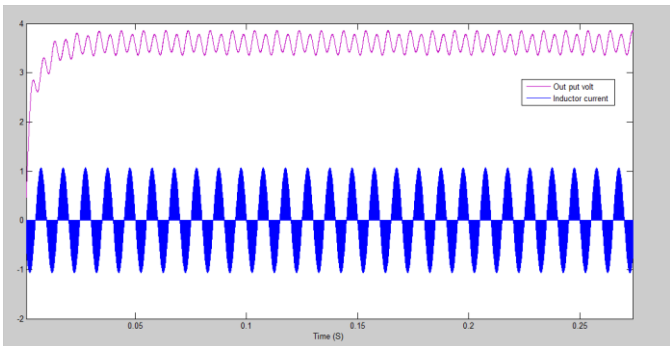


Fig 15: Output volt and inductors current

The pulse width will be reduced to 25% and the results are shown in figure (16).

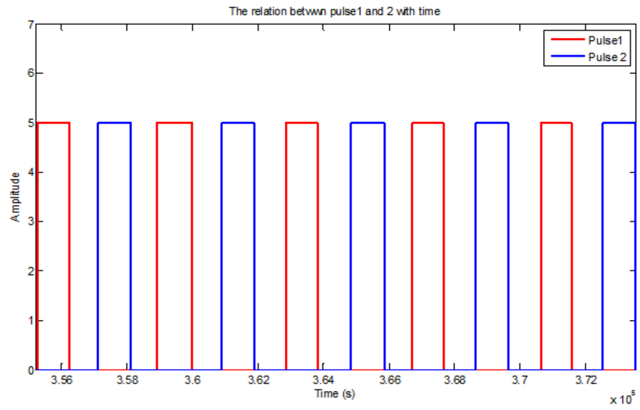


Fig 16: Pulse (1) and pulse (2) with 25% width and 10μs time delay

After the pulse width has been reduced to 25% the output volt has reduced to be 3v. This indicates the relation between the duty cycle and the output volt as shown in figure (17).

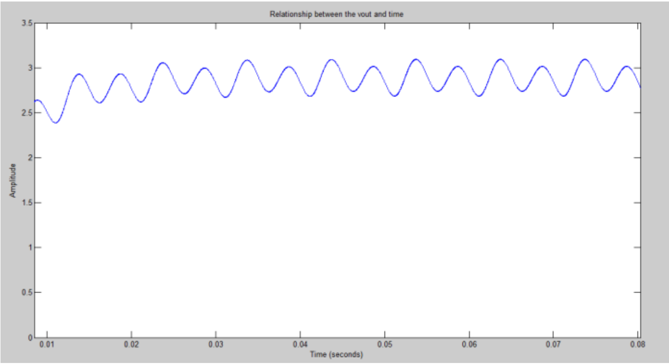


Fig 17: Output volt using 25% pulse width

Conclusion and further work

This paper has presented a single stage AC-DC topology for low volt harvesting applications. This topology has avoided the conventional bridge rectification in order to reduce the losses and achieve higher efficiency. The proposed converter uniquely combines both boost and buck boost converters which are connected in parallel. Avoiding bridge rectification makes this topology reliable in terms of efficiency and size. Single capacitor is used to filter the output and feed the load. The boost converter (S1, D1, and L1) is used to condition the positive half cycle of the input AC volt; whereas the buck boost (S2, D2, L2) is utilised to condition the negative half cycle of the input source. This topology has been selected from among different topologies which have been discussed with their disadvantages. The principal operations of the boost and buck boost converter have been discussed in four different models. Detailed analyses of the proposed topology have been carried out and the relation between various converter parameters is obtained. Matlab (Simulink) software has been used to simulate the converter. The converter successfully boosts the low AC volt (0.5v) in 100Hz to about 3DC volts. The circuit has been tested using two different pulse widths of the switching pulses.

This work done to this converter can be improved using many other techniques. Further work can be done by testing the converter in real environments and implementing it in real harvesting circuit to investigate the output efficiency of the converter. Moreover, future researchers need to go further to investigate and design integrated three phase electronic interface for energy harvesting applications.

References

[1]- Rao, B. and et al (2016) ` An Efficient AC-DC Step up Converter for Low voltage Harvesting Applications`. International Journal of Scientific Development and Research (IJSDR), Volume 1, Issue 7.

[2]- Vijayan, V. and Vinida,K. (2014) `A Review of AC-DC Boost Converters for Low Voltage Energy Harvesting`. International Journal of Emerging Technology and Advanced Engineering 4, 841-846

[3]- Kumar, V. and Mahesh, G. (2017) ‘An Efficient Direct AC-DC Converter for Low Voltage Energy Harvesting System’. International Journal of Scientific Development and Research (IJSDR), Volume 2, Issue 5.

[4]- Wang, H. Tang, and Y. Khaligh, A. (2013) `Bridgeless boost converter for low voltage energy application`. Journal of IEEE transaction on power electronic 28,5206-5214

[5]- Souza, L. and et al. (2022), `3SSC-A-Based Step-Down DC–DC Converters: Analysis, Design and Experimental Validation`. Energies **2022**, 15, 7710. https://doi.org/10.3390/en15207710.

[6]- Vijayan, V. and Vinida, K. (2014) `A Review of AC-DC Boost Converters for Low Voltage Energy Harvesting`. International Journal of Emerging Technology and Advanced Engineering 4, 841-846

[7]- Cheng, S. Yuan Rao, Y. and Arnold, D. (2011)`An active voltage doubling AC/DC converter for low voltage energy harvesting application’. Journal of IEEE transaction on power electronic 26.

[8]- Daya, R. Dwari, S. and Parsa, L. (2011) `Design and Implementation of a Direct AC–DC Boost Converter for Low-Voltage Energy Harvesting’. Journal of IEEE transaction on power electronic 58

[9]- Dwan, S. and Parsa, L. (2010) `An efficient step up AC-DC converter for low energy harvesting ` Journal of IEEE transaction on power electronic 25,2188-2199

[10]- Yang, Z. Lin, B. and Li, Z. (2021) `Recent progress in human body energy harvesting for smart bioelectronic system`. Fundamental Research journal homepage: http://www.keaipublishing.com/en /journals/fundamental-research/ Volume 1, Issue 3, May 2021, Pages 364-382.

[11]- Carne, G. (2022) ` On Modeling Depths of Power Electronic Circuits for Real-Time Simulation A Comparative Analysis for Power Systems`. Open access journal of power and energy. 10.1109/OAJPE.2022.3148777

[12]- K. Madhuri, A. Srujana.(2013)` Low Voltage Energy Harvesting by an Efficient AC-DC Step-Up Converter`. IOSR Journal of Electrical and Electronics Engineering.