DEVELOPMENT OF A LOW VOLTAGE AC TO DC CONVERTER FOR MESO AND MICRO ENERGY HARVESTERS

Farid Ullah Khan*, Tashfeen Ali*, Khubroo Jamil*

ABSTRACT

Energy harvesting is widely used for the operation of wireless sensor nodes. Most of the energy harvesters generated voltage levels are sinusoidal or random in nature, moreover, the output voltage levels these produce are in low (in mV range). For sensor operation, in order to convert this low AC voltage levels into relatively high DC voltage DC, a three stage Cockcroft Walton converter is developed. The paper presents fabrication and characterization of a 3 stage Low Voltage Cockcroft-Walton converter in an area of 5.5 x *3.3 cm*^{2}*. The converter was capable of converting a minimum AC voltage amplitude of 10 mV with a transformation factor of 6.5. The variation in the input frequency had almost no effect on the DC output voltage of the converter. Upon integration of the converter to different energy harvesters, the converter successfully rectified the AC or random output voltage signals of the harvesters into corresponding DC voltage.*

KEYWORDS: *AC to DC converter; Electrodynamic; Piezoelectric; Meso and micro energy harvesters, Low voltage; Wireless sensor node.*

INTRODUCTION

Batteries are usually the preliminary choice to power a sensing and monitoring system, however, due to their finite life cycle, maintenance issues and being an environmental hazard, these are losing the attention and the more versatile and environmental friendly alternative energy harvesting technique is gaining more interest and popularity. The environment around the sensor and monitoring systems contains various types of energies, for example, solar, wind, acoustic, thermal and vibrational energies. These available energy sources could be harvested to power the passive systems, such as wireless sensor nodes (WSNs). Energy harvesters are developed and commonly used to operate WSNs. A WSN is a sensor platform that is used to sense and monitor the physical phenomenon, such as pressure, temperature, sound level, acceleration, force and velocity. Normally, the limited life cycle batteries are used to operate these WSNs which restrict their applications in distant, buried and hazardous environments where it is difficult or even impossible to change or recharge the batteries. Increasing the battery's size for shelf life enhancement can be considered as an option, however, in case of meso and micro-scale WSNs this technique is discourage to adopt. With a WSN, if a primary battery is used, its life span is not more than a few months[1]. For continuous sensing and monitoring through WSNs, one should ensure that there is always energy available on the sensor's platform for operating the onboard instruments and for data transmission.

A typical WSN platform is composed of a number of electrical components, such as sensor, signal processing circuit, power management circuit, microcontroller, memory card, transmitter, antenna and a battery. Microcontroller is equipped with a predefined program and is used to control all the desired activities of the onboard components. A signal processing unit, after processing the data from the sensor, supplied the processed data to the microcontroller. A power management circuit acts to distribute the power from a battery to all the on shelf components. Memory card is utilized as data storage bank to store the data for certain period of time. An antenna ensures the transmission of sensor's data to the control room. Energy harvester is integrated with a WSN in order to transform it into a self power or autonomous WSN as shown in Figure 1. The energy harvester can harvest the useful energy from the ambient environment. The harvested energy which is in electrical form is then utilized through the power management circuit for operation and moreover, in case of surplus power is also stored in the battery for the situations where the harvester energy is either not available or not sufficient to completely operate the WSN.

* Institute of Mechatronics Engineering, University of Engineering & Technology, Peshawar, Pakistan

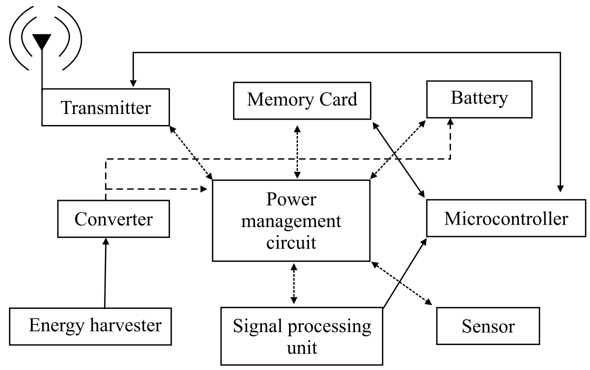


Figure 1. Autonomous wireless sensor node Architecture

Different kinds of energies can be utilized using several micro energy harvesters. In piezoelectric energy harvesters, piezoelectric materials produce voltage when these experience mechanical stress. quartz[2], polycrystalline ceramic and lead zirconate titanate are commonly used piezoelectric materials in these harvesters. Pyroelectric and thermoelectric materials are used to transform the ambient heat into electrical energy in thermal energy harvesters. In solar energy harvesters, photovoltaic cells are used for conversion of solar energy into electrical energy. Photovoltaic cells which in reality are a simple P-N junction (semiconductor) made up of P-type and N-type silicon wafers convert the sun's radiation into electrical energy[3]. Different factors, such as availability of light, cloud's presence, rain etc. are considered[4] while selecting photovoltaic cells for energy harvesting. Vibration based electromagnetic energy harvesters are also common nowadays. In these harvesters the magnetic flux linking a coil actually changes (electromagnetic induction) due to oscillations and thus voltage is generated. Voltage obtained from micro energy harvesters is either low or ultra-low and also in AC form. The AC output voltage of these harvesters needs to be converted into a reasonable DC voltage for the operation of micro sensors and autonomous WSNs.

The term 'Ultra low voltage' refers to the voltage level less than 100 millivolts. Vibration-based energy harvesters, acoustic energy harvesters, meso and micro scale solar energy harvesters, radio frequency (RF) energy generating units or electrodynamic energy harvesters all produce very low output voltage levels. This output low voltage levels generated by energy harvesters must be rectified and boosted into a suitable DC voltage levels in order to power passive systems[6].

In autonomous WSN (Figure 1) a converter is employed to perform the conversion of AC voltage generated by the energy harvester to DC voltage. Several AC to DC converters have been successfully developed and reported in literature.

LITERATURE REVIEW

Work has been performed in the past to develop low or low voltage converter. For a three phase micro generators, a converter was developed[7]. The developed converter is fabricated using CMOS, 0.35 µm technology on a wafer of 3 mm^2 size. Instead of diodes the converter was designed with the metal oxide semiconductor field effect transistors (MOSFETs). The reported converter was able to transform an AC inputs from 1 V to 3.3 V at an input frequency of 10–100 kHz. Moreover, an efficiency of 90% was achieved with the converter.

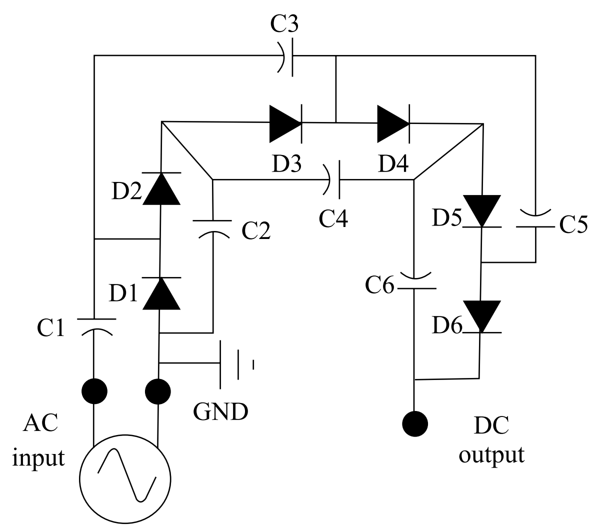


Figure 2. Three stage Cockcroft Walton converter

An low voltage, low power, high precision digitally tunable trans-conductor converter[8] was developed successfully. Using the high impedance voltage-mode input stage with wide input common mode voltage range, the full-wave converter was able to achieve both high accuracy and easy interface. The converter was able to show promising results under supply AC voltage from 0.5 V to 1.8 V, and a wide frequency range from 0 to 25 MHz. A converter[9] was designed to trade-off for low power and low voltage for sensor utilization in various biomedical applications. The developed converter was reported to consume 90 nW power and operate from a supply AC voltage of 1 V to 1.5 V. CMOS 0.35µm technology was used for the fabrication of the prototype circuit. Operational amplifiers were used as building blocks. The converter was able to convert input voltage with a frequency of maximum 100 Hz. An active converter was developed[10], using 0.5 µm CMOS technology. The converter was a MOSFET-based full-wave converter. The converter was found to convert a supply AC voltage amplitude from 0.65 V to 2.5 V, with an input frequency ranging from 1 Hz to 100 kHz. For the converter a maximum efficiency of 85% was reported. Moreover, the prototype converter had the ability to automatically enter into standby mode with almost zero power consumption for voltage levels below 0.6 V. The footprint area of the converter was about 0.026 mm^2 and a maximum power of 380 µW was consumed at an input voltage of 1 V and a load resistor of 2 kΩ. A two stage converter circuit was developed, with comparators[11]. The voltage drop over the converter was found to be tens of millivolts, which resulted in efficiency over 90%. CMOS 0.35 µm technology was utilized for fabrication of the prototype circuit. A maximum power consumed by the converter was 266 nW at 500 mV input voltage. Minimum operating voltage for the converter was reported as 380 mV, and it could convert input frequency up to 10 kHz. The active area of the converter was 380 x 190 μm^2. A temperature compensated diode converter[12] was also produced to minimize the forward voltage drop while keeping the reverse leakage flow on lower side. CMOS 0.35 µm fabrication technology was adopted for the development. The reported converter was optimized for an input frequency of 13.56 MHz. For an input AC voltage of 500 mV at 13.56 MHz frequency the converter was able to deliver an output DC voltage of 2.5 V and 35 µW power at 180 kΩ resistance. A converter[13] was designed and developed specifically in application to vibration-based energy harvesters those have a very random and time-fluctuating voltage waveform. The circuit was produced with comparators, and was able to convert the minimum voltage of 5 mV, and an input frequency ranging from 1 to 500 Hz. For an input voltage greater than 250 mV, the converter was able to deliver efficiency greater than 80%. The output power was calculated to be ranging from 0.1 to 10 mW. An active diode converter[14] was developed as an application to electromagnetic energy harvesters. The converter was reported to have an efficiency of 90% for a wide range of input voltages ranging from 0.48 V to 3.3 V. CMOS 0.35 µm fabrication technique was used for the circuit. The converter consumed low power of only 10 µW during operation.

In this work a Cockcroft Walton converter (CWC) topology is used to develop a converter for low applications. A CWC transforms low AC voltage into high DC voltage and moreover, is capable of providing a uniform current during operation[15]. Cockcroft Walton converters have applications in several equipment and appliances, such as, in cathode ray tube (CRT) televisions and liquid crystal display (LCD) monitors.

Normally, in CWC, two diodes and two capacitors constitute one stage. Stages need to be increased in order to get higher output voltage levels. The voltage across each stage of the circuit is equal to twice the peak input voltage[16] and output can be obtained at any stage from the converter. Output voltage

$$V_{out} = 2 \times N \times V_{in} \quad (1)$$

after being through all the stages depends on the peak input voltage V_{in} and the number of stages N utilized in the converter. e.g. if the peak input voltage is 5 V, then after being through three stages Cockcroft Walton converter, the output will be 30 V approximately. Moreover, the output voltage also depends on the type of waveform (rectangular/square/sine wave) of the input voltage signal. The output voltage is higher for square wave, low for triangular waveform and moderate for sine waves. This is actually, due to the time available for peak voltage which charges the capacitor.

A circuit topology of a three stage CWC is shown in Figure 2. The operation of the circuit can be explained[16] by assuming an alternating voltage V_i supplied as input and then observing its transformation behaviour during different stages of the circuit. During the negative cycle the diode D1 will be forward biased to charge capacitor C1 to voltage V_i. However, during the positive cycle the voltage from the source and the capacitor C1 being in series will double up to $2V_i$ and the diode D2 being forward biased also starts charging capacitor C2 to $2V_i$. The voltage $2V_i$ across capacitor C2 serves as an input to the second stage and during the negative cycle the capacitor C3 is charged by diode D3 to $2V_i$. Similarly, in the next positive cycle, the capacitor C4 is charged by capacitor C3 through diode D4 to a voltage level of $2V_i$. Being in series, the two capacitors C2 and C4 will double up the voltage to $4V_i$. The same will be the case for third stage of the circuit and adding the voltage levels will amplify the voltage to $6V_i$. The main advantage to this design of the circuit is the arrangement of the capacitors in series to the load due to which the voltage is amplified.

FABRICATION

The circuit diagram of the developed ultra low voltage CWC is shown in Figure 2. The three stages of the converter are arranged in such a way to accommodate the minimum area on a printed circuit board (PCB). For the low and ultra low voltage conversion, low voltage, surface mount, Schottky diodes (Pmeg2010aeb) were used. Moreover, 330F, 25 V, surface mount aluminum capacitors are selected to be connected with these diodes. For the PCB development of the CWC an Express PCB was utilized as an electronic computer aided design (ECAD) to produce a circuit layout Figure 3 (a). First of all track pads for the diodes were created in the CAD software. The width of the diode is 0.85 mm, however, to provide a greater surface area for diode to mount upon, the track pad of an area of 1.5 mm^2 are selected. The distance between two pads is kept 0.5 mm as the length of the diode is 1.25 mm. Track pads for the capacitors are designed similarly. The track pads of diodes and capacitors are then connected with the help of 0.76 mm trace lines, as shown in Figure 3.

Once the ECAD layout design of the CWC was complete, the circuit was printed on a thin photographic paper using a laser inkjet printer, Figure 4 (a). The piece of copper clad PCB sheet on which the CWC had to be printed upon was cleaned with sandpaper to make sure that the top copper oxide layer is removed, Figure 3 (b). The sheet was washed thoroughly with distilled water and dried with compressed air. The photographic paper was then placed on the copper clad sheet with the printed circuit in contact with the copper sheet. An electric iron was then placed on the photographic paper for about ten minutes that resulted in pattern transfer from the photographic paper on the copper clad sheet, Figure 3 (c) and Figure 4 (b). The areas with broken trace lines were covered with a permanent marker to ensure the whole circuit is complete without any broken trace line.

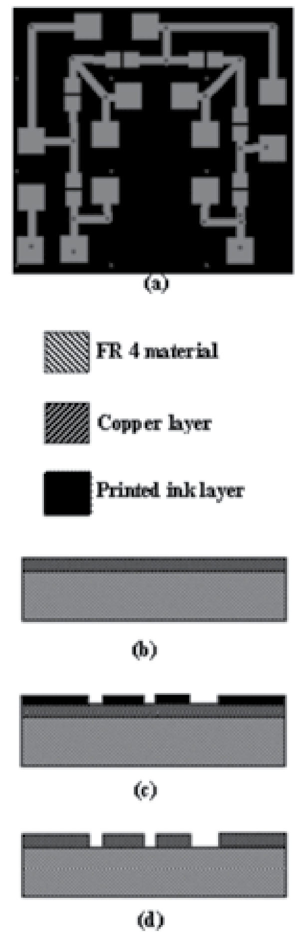


Figure 3. Fabrication process: (a) PCB layout for the converter, (b) Cross-sectional view of copper clad sheet, (c) Ink printed on copper clad sheet, (d) Copper clad sheet after etching and ink removal process

For etching, solid Ferric Chloride was dissolved in warm water, Figure 4 (c). The copper clad sheet with the circuit pattern was placed in the bowl containing the ferric chloride solution. The solution was constantly stirred and then 10 minutes later the copper clad sheet was taken out of the solution. During etching all the copper was removed except where the circuit layout was patterned, Figure 4(d). The printed circuit pattern was then erased with a sand paper, revealing the copper traces on the PCB, Figure 3 (d) and Figure 4(e). The capacitors (Figure 4(f)) and diodes (Figure 4(g)) were then carefully mounted and soldered on the developed PCB (on their mentioned track pads), Figure 4(h).

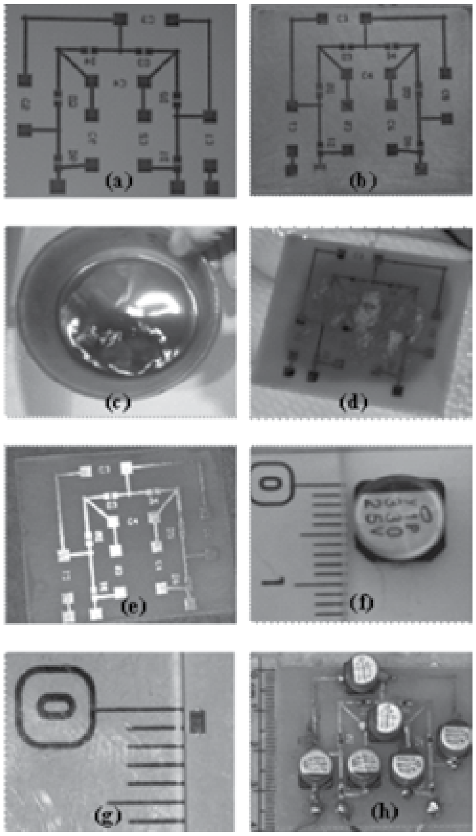


Figure 4. Fabrication of ultra low voltage CWC: (a) Circuit printed on photographic paper, (b) Circuit pattern transfer on a copper clad sheet, (c) FeCl3 etching Solution, (d) partially etched board, (e) completely etched PCB, (f) Aluminum capacitor, (g) Ultra-Low Voltage diode, (h) developed converter circuit

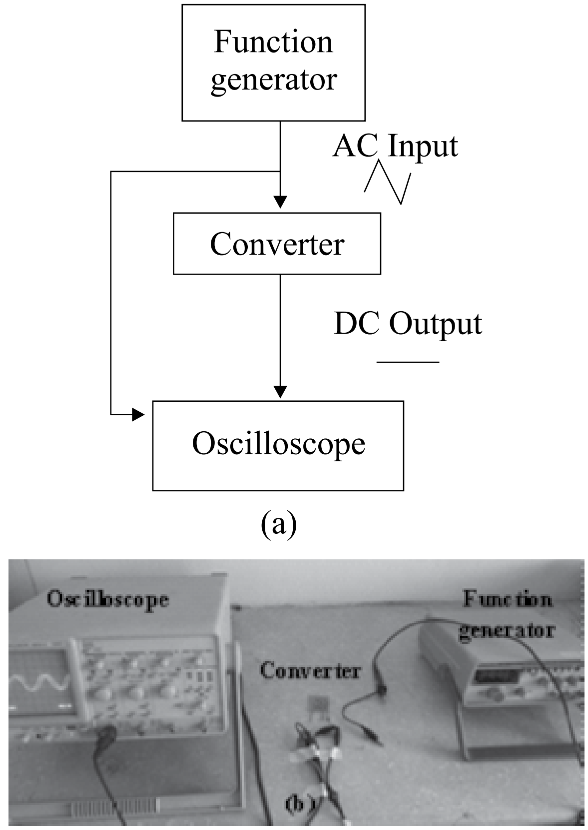


Figure 5. (a) Experimental setup block diagram, (b) Experimental setup during in-lab characterization

EXPERIMENTATION AND RESULTS

In-lab characterization of the prototype circuit

Figure 5 shows the experimental setup used for the in-lab characterization of the developed CWC. During in-lab testing, instead of energy harvester, a function generator was used to provide input voltage waveforms of various amplitudes and frequencies. Oscilloscope was used to observe the input and out voltage signals' different parameters, such as, frequency, amplitude. Sinusoidal waveform was provided as an input throughout the in lab characterization.

Figure 6 shows a plot between input and output voltage. The prototype circuit due to its 330 μF capacitors could convert lower voltages (millivolts) as well as higher voltages. The maximum input provided to converter was 1 V AC, which was efficiently converted and amplified to 6 Volts DC, which is in exact accordance with Equation 1. The minimum input voltage amplitude that could be converted with the developed circuit was 10 mV, the corresponding output DC voltage at the reading was 30 mV.

The converter was also tested over a number of different frequencies of the input voltage in order to observe its effect on output voltage. It was noticed that changing input the frequency has no effect on the output voltage signal of the circuit. As seen, the output signal is almost constant for every value of input frequency as shown in Figure 7.

Output DC voltage as a function of load resistance is shown in Figure 8. During this experimentation, various resistors were connected as load and the voltage across each resistor was recorded. The output voltage was witnessed to be constant at 560 Ω for almost all input voltages.

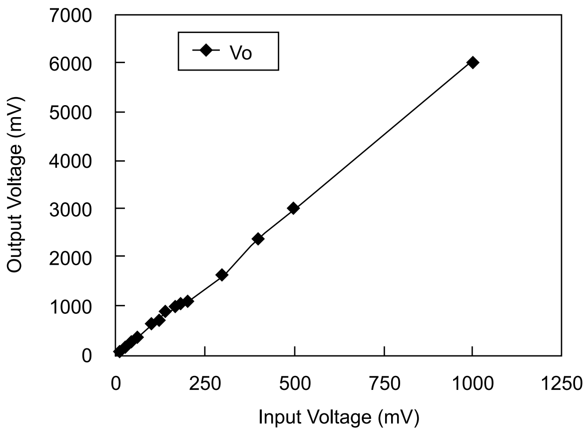


Figure 6. Input AC voltage amplitude versus output DC voltage

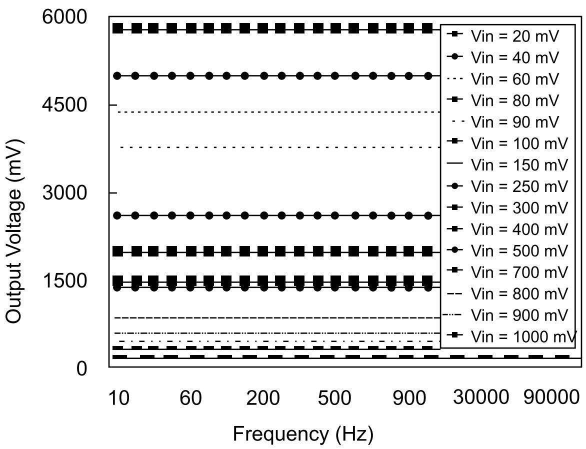


Figure 7. Output DC voltage versus input AC voltage frequency

The power

$$P = \frac{(V_{DC})^2}{R_L} \qquad (2)$$

delivered to the load R_L was calculated with the help of measured DC output voltage V_{DC}.

Load power as function of the load resistance is plotted in Figure 9. The characterization is performed under an input voltage frequency of 300 Hz. Irrespective of the input voltage amplitude, maximum load power was obtained for a load resistor of 180 Ω, which showed that for maximum power transmission through the circuit; if possible the load resistance of 180 Ω should be kept.

Transformation factor (V_{output}/V_{input}) versus load resistance is shown in Figure 10. Maximum transformation factor obtained was 6.5 for an input voltage of 400 mV. However, the least transformation factor obtained was 1.4 and is for an input AC voltage of 20 mV at load resistance of 100 Ω.

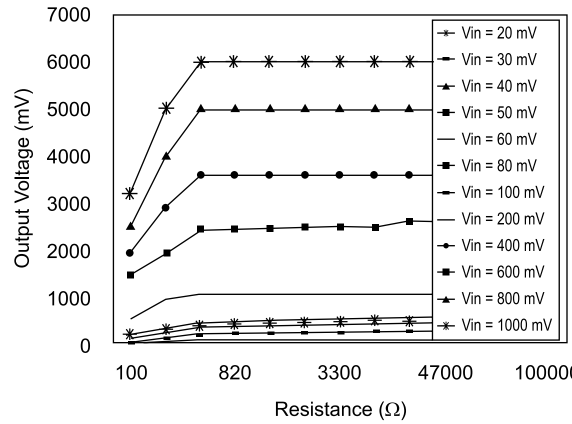


Figure 8. Output DC voltage versus load resistance

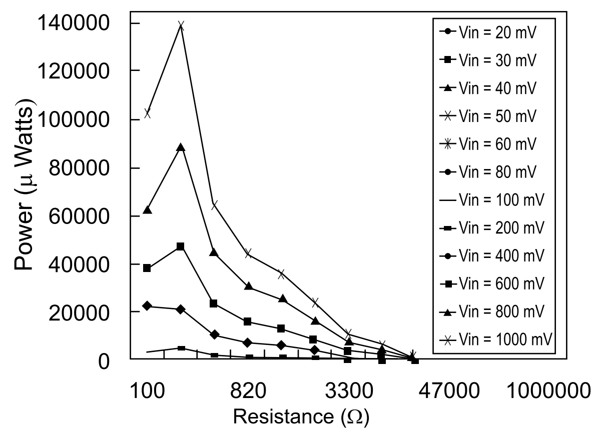


Figure 9. Output load power versus load resistance

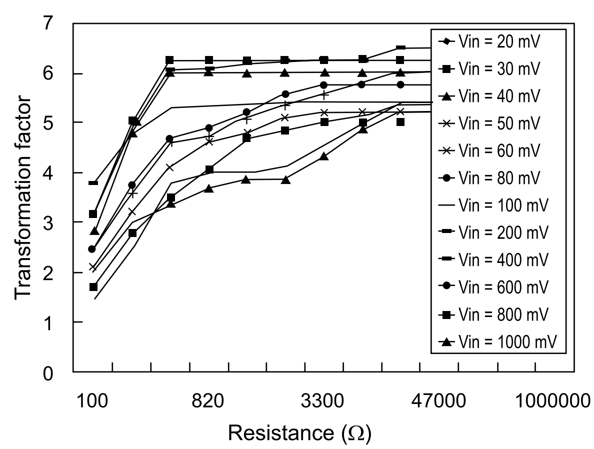


Figure 10. Transformation factor versus load resistance

The summary of the characterization of the developed AC to DC converter is provided in Table 1.

Table 1. Converter characterization summary

Measured parameter	Value
Minimum AC voltage rectified	**10 mV**
Input AC voltage range	10 mV – 1 V
Input frequency range	10 Hz – 100 kHz
Load resistance range	100 – 1000 kΩ
Optimum load	180 Ω
Maximum transformation factor	6.5

INTEGRATION OF CONVERTER WITH ENERGY HARVESTERS

The developed AC to DC converter was also tested in a real environment by integrating it to different energy harvesters. The energy harvesters to which the circuit is connected included an acoustic energy harvester[17], an electrodynamic energy harvester (extracting energy from the stray magnetic field around a power cable), a piezoelectric acoustic energy harvester and human motion-based electromagnetic energy harvester. The experimental setup used for the characterization of the converter when is connected to an energy harvester is depicted in Figure 11. With the setup comprised of an energy harvester, converter, NI data acquisition (DAQ) card and laptop computer. The analog signals from the energy harvester and the converter are simultaneously acquired with the DAQ card and were observed and analyzed in NI LabView software.

The converter was integrated with two types of acoustic energy harvesters, an electromagnetic based acoustic energy harvester and a piezoelectric based acoustic energy harvester. The electromagnetic based acoustic energy harvester consisted of a permanent magnet and a wound coil, and was able to convert the ambient acoustic energy into AC voltage through the Faraday law of electromagnetism. A 8 kW electric generator was used as an acoustic energy source with sound pressure level ranging from 30 to 90 dB as shown in Figure 12. The data was observed on laptop with the help of DAQ card. The piezoelectric acoustic energy harvester was tested with the generator and a motor bike. The electromagnetic handheld device was able to harvest energy from human body during walking.

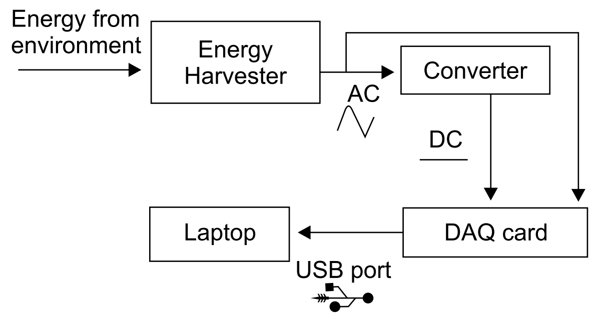


Figure 11. Experimental setup for real scenario characterization (converter integrated to an energy harvester)

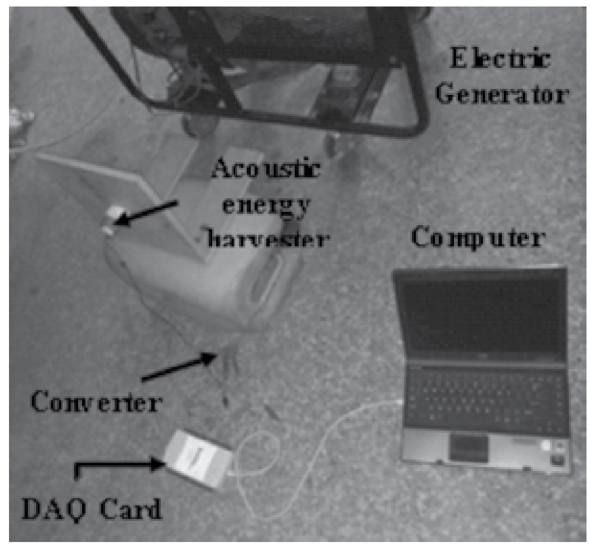


Figure 12. Setup for converter characterization when the converter is connected to an electromagnetic acoustic energy harvester

The output of an electromagnetic acoustic harvester was narrow band and random in nature. A maximum voltage amplitude of 17 mV was produced by the acoustic energy harvester a. The input from the energy harvester was converted and amplified to 75 mV DC voltage as shown in Figure. 13.

The developed converter performance is also analyzed when it is connected to a piezoelectric based acoustic energy harvester as shown in Figure 14 and Figure 15. During this experiment, the acoustical noise of an electric generator and a motor bike were used as the acoustical energy sources for the acoustic energy harvester When

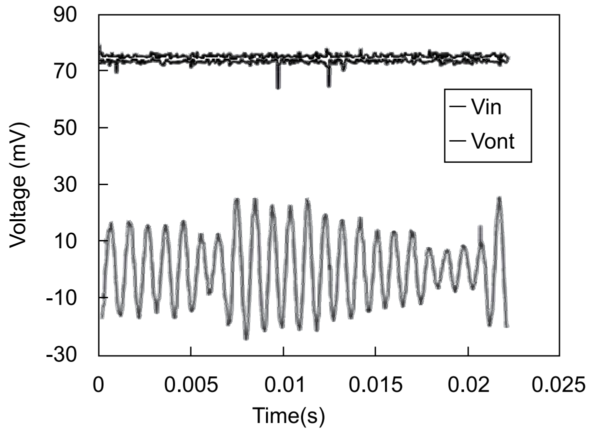


Figure 13. AC input to the converter from acoustic energy harvester and rectified DC output.

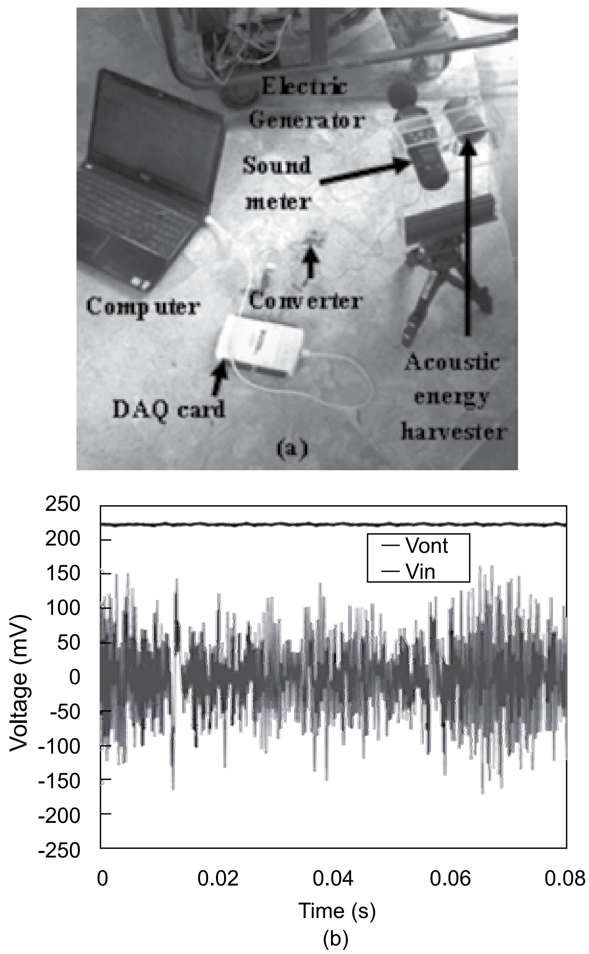


Figure 14. Integration of converter circuit with a piezoelectric acoustic energy harvester: (a) Setup for the characterization of the converter when energy harvester is generating power from the noise of an electrical generator, (b) Input random voltage signal to the converter and rectified DC output

the piezoelectric acoustic energy harvester was placed near the electrical generator (Figure 16(a)), the converter was able to convert and amplify the random voltage with maximum amplitude of 150 mV into 220 mV DC voltage as shown in Figure 16 (b).

However, when the piezoelectric based acoustic energy harvester was subjected to acoustic noise created by a motorbike, Figure. 15 (a), the random output of the harvester had output maximum amplitude of about 96 mV, which was converted and amplified to 150 mV DC voltage by the developed converter as shown in Figure 15 (b).

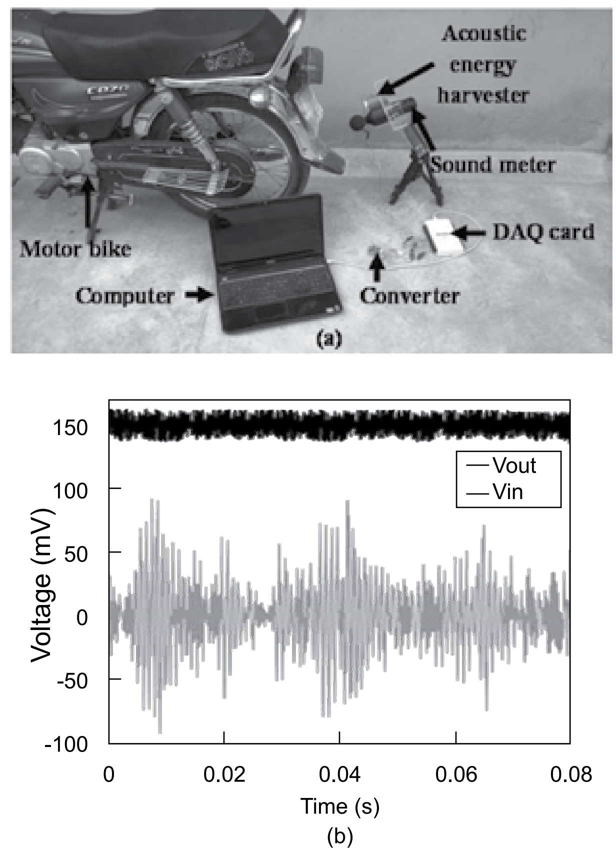


Figure 15. Integration of converter circuit with a piezoelectric acoustic energy harvester: (a) Setup for the characterization of the converter when energy harvester is generating power from the noise of a motorbike, (b) Input random voltage signal to the converter and rectified DC output

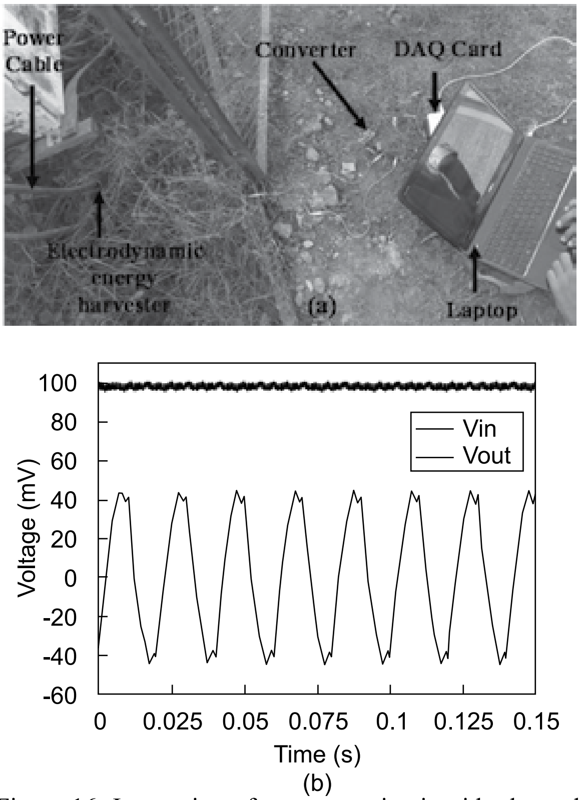


Figure 16. Integration of converter circuit with electrodynamic energy harvester: (a) Setup for the characterization of the converter when it is connected to a stray magnetic field electrodynamic energy harvester, (b) AC input to the converter from electrodynamic energy harvester at a cable's current level of 21 A and the converted DC output

The electrodynamic energy harvester was capable of converting a stray magnetic field around a power cable into useful electrical energy and produced an AC output. Measurements from the electrodynamic energy harvester were obtained at various current levels in the power cable. At a cable current level of 21 A, the harvester's AC output to the converter and converted DC output voltage are plotted in Figure 16. The converter rectified an AC input voltage of amplitute 40 mV into 80 mV DC voltage. In the rectified DC signal there were few ripples which were attributed to the low frequency electrical noise present during characterization.

Figure 17 shows the AC inputs to the converter (from the electromagnetic energy harvester) and the corresponding DC output voltage levels at a cable current levels of 27 A and 30.3 A respectively. At 27 A cable's current the harvester's 50 mV output voltage was converted to

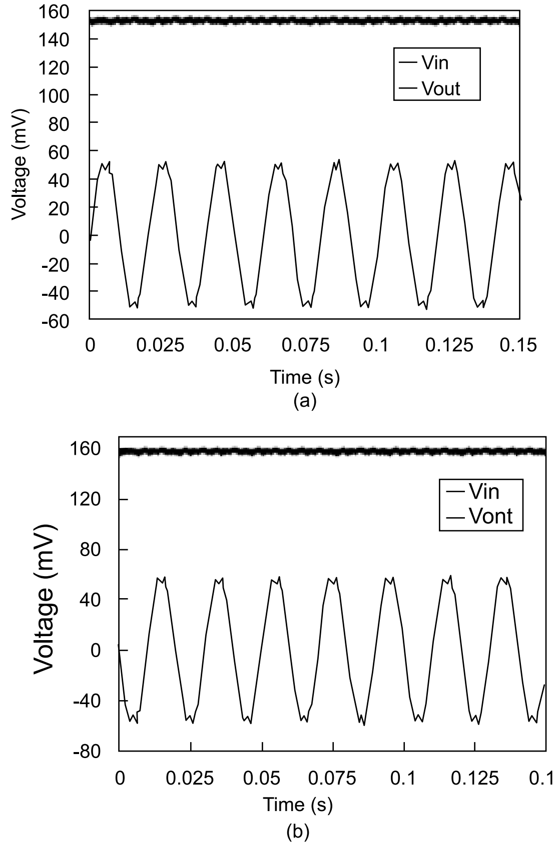


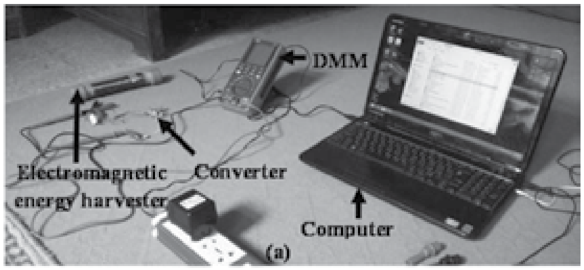
Figure 17. (a) AC input to the converter at a current level of 27 A and corresponding DC output voltage, (b) AC input to the converter at a current level of 30.3 A and the corresponding DC output voltage.

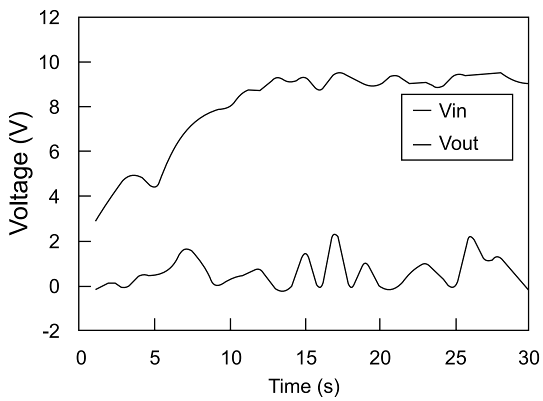
111 mV DC, as presented in Figure 17 (a). However, at current level of 30.3 A in the power line, the harvester's n output voltage of 60 mV was rectified into the output DC voltage of 160 mV, Figure 17 (b).

A hand-held electromagnetic energy harvester developed to harvest energy from human motion was also integrated with the converter. The harvester was shaken by hand with an average frequency of about 6.1 Hz and the generated output voltage signal was supplied to the developed converter. The setup is shown in Figure 18 (a). The measurements during this characterization are shown in Figure 18 (b). The generated voltage that had a maximum amplitude voltage of 2.3 V was rectified to a DC voltage of 9.49 V.

COMPARISON OF REPORTED CONVERTERS

Comparison of this work has been performed with





(b)

Figure 18. Integration of converter circuit with a hand-held electromagnetic energy harvester: (a) Setup for the characterization of the converter when energy harvester is generating power from the human hand motion, (b) Input random voltage signal to the converter and rectified DC output voltage

the low voltage AC to DC converter developed in past. The low voltage converters can be compared with different criterions such as minimum AC voltage rectified, minimum input frequency, power consumption, efficency, tranformation factor and operational frequency range. Moreover, number of energy harvesters the converter can be integrated can also be set as a comarison criteria. Most meso or micro-scale energy haervsters have low output voltage levels and sometimes these are developed for low frequency operation. Almost all of the converters have the ability to process low frequency voltage signals except[12] in which case the frequency was found to be 13.56 MHz. The converter presented in this work has the advantage of procesing a wide range of frequencies from a few Hz to MHz. The ability to rectify low voltage signal that is below 0.5 V was seen to lack in some of the reported converters[7,9,10]. A broad range of input voltage can be considered as a main advantage for this work in comarison to other reported low volatge converters developed in the past which could only process a small range of input AC voltage levels. For the developed converters an efficiency greater than 80 % is reported, which is mainly contributed due to the design of converter. The efficiency of the AC to DC converter developed in this work is about 60%.

Table 2. Comparison of AC to DC converters

Ref.	Min. V_{in} (V)	V_{in} range (V)	F_{in} range (Hz)	Power Consumption (W)	Eff. (%)	Integration of converter with energy harvesters
7	1	1 - 3.3	10 - 100 k	-	90	Electromagnetic generator
8	0.5	0.5 - 1.8	1 – 25 M	-	-	-
9	1	1 - 1.5	1 - 100	90 n	-	Electromagnetic energy harvester
10	0.6	0.65 - 2.5	1 - 100 k	380 µ	82.4	Electrodynamic vibration energy harvester
11	0.38	0.38 - 0.5	0 - 10 k	266 n	90	Electromagnetic vibration energy harvester
12	0.5	0 - 0.5	13.56 M	-	-	-
13	0.005	0.005 - 0.5	1 - 500	10 m	80	Electromagnetic vibration energy harvester
14	0.48	0.48 - 3.3	-	10 µ	90	Electromagnetic energy harvester
This work	0.01	0.01 - 1	10 - 1 M	32 m	61	Electrodynamic, Piezoelectric, electromagnetic energy harvester

CONCLUSIONS

The low voltage AC to DC converter circuit for meso and micro energy harvesters was successfully developed. The converter was characterized in lab as well as with vibration, motion and acoustic based energy harvesters. The reported converter was found suitable for most of the energy harvesters with low AC output voltage (in mV range). A voltage, as low as 10 mV was successfully converted with the developed circuit. Moreover, converter was also able to convert a large range of input voltage (from 10 mV to 1 V) to a suitable output DC voltage. Maximum transformation factor of 6.5 was obtained for the converter. For maximum power transmission the optimum load of 180 Ω was recorded. Results were also obtained with a very broad range of input frequencies, which is also considered as an advantage for the developed circuit. Furthermore, the converter also successfully operated at an input AC voltages with low frequency such as 10 Hz.

REFERENCES

1. *Andrew Townley –Electrical Engineering, University of Pennsylvania Advisor: Gianluca Piazza "Vibrational Energy Harvesting using MEMS Piezoelectric Generators".*

2. *T. Dikshit, D. Shrivastava, A. Gorey, A. Gupta, P. Parandkar and S. Katiyal, 2010. "Energy Harvesting via Piezoelectricity," BIJIT - BVICAM's International Journal of Information Technology, vol. II, no. 2, pp. 265-270.*

3. *Z. L. Wang and W. Wu, 2012. "Nanotechnology-Enabled Energy Harvesting for Self-," Angewandte Chemie International Edition, vol. 51, no. 47, pp. 11700-11721.*

4. *S. Chalasani and J. M.Conrad, 2008. "A Survey of Energy Harvesting Sources for Embedded Systems," in Southeastcon, Huntsville, IEEE, pp. 442-447.*

5. *C. G. Gonsalez, V. R. Franco, M. J. Brennan, S. d. Silva and V. L. Junior, 2010. Energy Harvesting using Piezoelectric and Electromagnetic," in 9th Brazillian Conference on Dynamics, Control and their Applications, pp. 1166-1171.*

6. *D. Grgić, T. Ungan, M. Kostić and L. M. Reindl, 2009. "Ultra-Low Input Voltage DC-DC Converter for Micro Energy Harvesting," in PowerMEMS, Washington DC, pp. 265-268.*

7. *Raisigel, H., J.-C. Crebier, Y. Lembeye, J. Delamare, and O. Cugat. 2007. "Autonomous, Low Voltage, High Efficiency, CMOS Rectifier for Three-Phase Micro Generators." The 14th International Conference on Solid-State Sensors, Actuators and Microsystems. Lyon, France,: IEEE, pp. 883-886.*

8. *Dong Han, and Yuanjin Zheng 2009. "A Low-Voltage Low-Power High Precision Digitally Tunable Transconductance Converter." IEEE pp. 368-371.*

9. *Rodriguez-Villegas, Esther, Philip Corbishley, Lujan-Clara Martinez, and Sanchez- Trini Rodriguez. 2009."An ultra-low-power precision converter for biomedical sensors interfacing." Sensors and Actuators A: Physical, pp. 222-229.*

10. *Rao, Yuan, and P. David Arnold 2010. "An Input-Powered Active AC/DC Converter with Zero Standby Power for Energy Harvesting Applications." IEEE, pp. 4441-4446.*

11. *Peters, Christian, Jonas Handwerker, Dominic Maurath, and Yiannos Manoli 2011. "A Sub-500 mV Highly Efficient Active Converter for Energy Harvesting Applications." IEEE Transactions on Circuits and Systems—I: Regular Papers, Vol. 58, No. 7, pp. 1542-1550.*

12. *Xu, Hongcheng, and Maurits Ortmanns 2011. "A Temperature and Process Compensated Ultralow-Voltage Converter in Standard Threshold CMOS for Energy-Harvesting Applications." IEEE Transaction on circuits and systems--II: Express Briefs, Vol. 58, No. 12, pp. 812-816.*

13. *Cheng, Shuo, Ying Jin, Yuan Rao, and David P. Arnold 2010. An Active Voltage Doubling AC/DC Converter for Low-Voltage Energy Harvesting Applications." IEEE Transaction on Power Electronics, Vol. 26, No. 8, pp. 2258-2265.*

14. *Dominic Maurath, Philipp F. Becker, Dirk*

Spreemann, and Yiannos Manoli 2012. Efficient Energy Harvesting With Electromagnetic Energy Transducers Using Active Low-Voltage Rectification and Maximum Power Point Tracking " IEEE, Journal of solid-state circuits, Vol. 47, No. 6, pp. 2258-2265.

15. *M. Suzaini and M. Hamdan 2008. Design, Simulate And Construct 15kv Cockcroft-Walton Voltage Multiplier.*

16. *R. Moghe, D. Divat and F. Lambert 2011. Powering Low-Cost Utility Sensors using Energy Harvesting," in 14th Europian Conference, Brimingham, pp. 883-886.*

17. *Khan, Farid Ullah, and Izhar 2013. Acoustic-Based Electrodynamic Energy Harvester for Wireless Sensor Nodes Application." International Journal of Materials Science and Engineering Vol. 1, No. 2, pp. 72-78.*