Research Journal of Applied Sciences, Engineering and Technology 8(15): 1710-1718, 2014
DOI:10.19026/rjaset.8.1154
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: July 01, 2014 Accepted: August 26, 2014 Published: October 15, 2014

Research Article

Performance Evaluation a Developed Energy Harvesting Interface Circuit in Active Technique

Ramizi Mohamed, Mahidur R. Sarker and Azah Mohamed
Department of Electrical, Electronic and System Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM, Bangi, Malaysia

Abstract: This study presents the performance evaluation a developed energy harvesting interface circuit in active technique. The energy harvesting interface circuit for micro-power applications uses equivalent voltage of the piezoelectric materials have been developed and simulated. Circuit designs and simulation results are presented for a conventional diode rectifier with voltage doubler in passive technique. Most of the existing techniques are mainly passive-based energy harvesting circuits. Generally, the power harvesting capability of the passive technique is very low. To increase the harvested energy, the active technique and its components such as MOSFET, thyristor and transistor have chosen to design the proposed energy harvesting interface circuit. In this study, it has simulated both the conventional in passive circuit and developed energy harvester in active technique. The developed interface circuits consisting of piezoelectric element with input source of vibration, AC-DC thyristor doubler rectifier circuit and DC-DC boost converter using thyristor with storage device. In the development circuits, it is noted that the components thyristor instead of mainly diode available in conventional circuits have chosen. Because the forward voltage potential (0.7 V) is higher than the incoming input voltage (0.2 V). Finally, the complete energy harvester using PSPICE software have designed and simulated. The proposed circuits in PSPICE generate the boost-up DC voltage up to 2 V. The overall efficiency of the developed circuit is 70%, followed by the software simulation, which is greater than conventional circuit efficiency of 20% in performance evaluator. It is concluded that the developed circuit output voltage can be used to operate for the applications in autonomous devices.

Keywords: AC-DC rectifier, autonomous devices, DC-DC boost converter, energy harvesting, piezoelectric element

INTRODUCTION

The development of low-power electronic devices such as microelectronics and wireless sensor nodes, as well as the global interest in the concept of "piezoelectric", the topic of energy harvesting from the environment has received much attention with the recent growth. Harvesting energy for powering micro-power devices have been increasing in popularity. These types of devices can be used in sensor networks or in embedded applications where battery replacement is unrealistic. The use of batteries, however, presents several problems are including the cost of battery replacement and limitation imposed by the need of suitable access to the device for battery replacement purposes. Wireless sensor nodes are often used in remote locations or embedded into a structure, therefore, access to the device can be difficult or impossible. By harvesting ambient energy Piezoelectric materials have received the most attention for obtaining electric energy from the surrounding an electronic device, energy harvesting solutions have the ability to provide permanent power sources that do not require periodic replacement. Such systems can operate in an autonomous, self-powered manner, reducing the costs associated with battery replacement and can easily be placed in remote locations or embedded into host structures.

In this study, different methods of energy harvesting from the environment are explored as alternative sources of energy for devices. Some of the most popular energy extractions used in electronic devices today is Radio Frequency (RF) and thermal/vibrational energy extraction. Among the various modes of energy harvesting, vibration energy harvesting is the most versatile technique developed in the literature (Guan and Liao, 2007). Three main mechanisms of vibration-to-electrical energy conversion exist including electrostatic, electromagnetic and piezoelectric transducer as shown in Fig. 1. Among the three modes of vibration harvesting, piezoelectric energy harvesting has received the most attention, with three review articles dedicated to recent research on piezoelectric transducer (Sodano

Corresponding Author: Ramizi Mohamed, Department of Electrical, Electronic and System Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM, Bangi, Malaysia, Tel.: +6-03-8911 8408

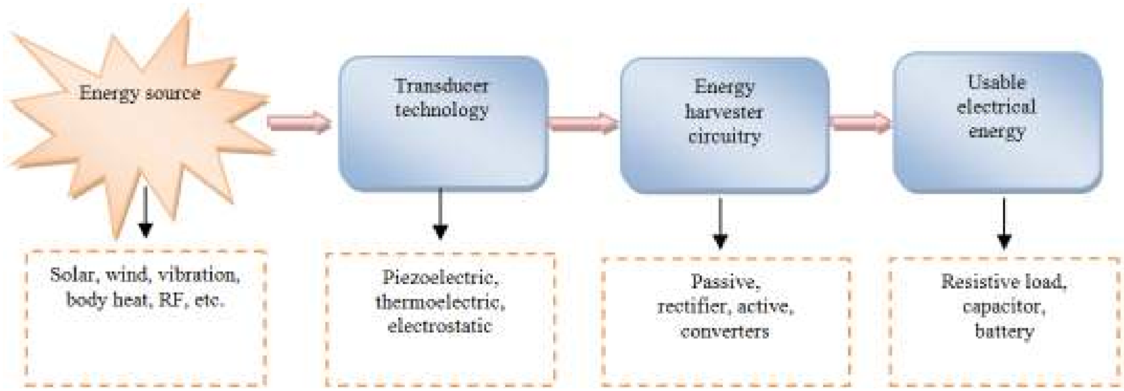

Fig. 1: Energy harvesting block diagram

Table 1: Various vibration sources with their characteristic frequencies and acceleration

Vibration source	Frequency of peak (Hz)	Peak acceleration (m/sec^2)
Kitchen blender casing	121	6.40
Clothes dryer	121	3.50
Door frame (just after the door closes)	125	3
Small microwave oven	121	2.25
HVAC vents in office building	60	0.20-1.50
Wooden deck with people walking	385	1.30
Bread maker	121	1.03
External windows (size 2×3 feet) next to a busy street	100	0.70
Notebook computer while the CD is being read	75	0.60
Washing machine	109	0.50
Second story of wood frame office building	100	0.20
Refrigerator	240	0.10

et al., 2004; Anton and Sodano, 2007; Priya, 2007). Piezoelectric vibration harvesting is attractive mainly due to the simplicity of piezoelectric transducer and the relative ease of implementation of piezoelectric systems in a wide variety of applications as compared to electrostatic or electromagnetic methods (Roundy, 2003). There are two types of energy harvesting appear; namely, passive and active. The passive methods are well established but the performance of the passive method is much lower than the energy potential of the piezoelectric devices. So generally the power harvesting ability of the passive technique is very low. The active energy harvest idea, represented by the Synchronized Switch Harvesting on Inductor (SSHI) technique by inverting the piezoelectric voltage in phase with the device velocity, improves performance over the active techniques and systematically increases the efficiency of energy harvesting dramatically.

Each type of vibration has specific interests based on the applications in terms of sensing, actuation and energy harvesting. Free vibrations meanwhile challenges one in designing a vibration energy using non-resonant which utilize impact energy or a simple kinetic energy (e.g., harvesting energy from shoe, backpack, etc.) (Mateu and Moll, 2005; Grastrom *et al*., 2007). Forced vibrations have a continuous external forcing function allowing the structure to vibrate in a certain pattern as described earlier. This pattern of vibration results in a specific frequency and amplitude of the vibrating structure permitting one to design a vibration energy harvesting device with a natural frequency same as the source frequency to be in resonance. Some on common domestic and acceleration application (Umeda *et al*., 1996; Gao and Cui, 2005) as shown in Table 1 to exhibit that vibrations are present ubiquitously.

MODELLING OF ENERGY HARVESTING INTERFACE CIRCUIT IN ACTIVE TECHNIQUE WITH CONVENTIONAL IN PASSIVE TECHNIQUE

The preliminary information of piezoelectric energy harvester system such as energy harvesting block diagram, circuits and simulation results by PSPICE software are provides in this section. These characteristics of the piezoelectric based harvester are mentioned through selective block diagram. A simple AC-DC thyristor rectifier circuit is present to convert AC signal to DC and DC-DC boost Converter is presented to step-up the rectifier voltage. The rectifier output voltage is very low as well as it has not yet turned into reality to use the voltage any application without (Step-up).

Piezoelectric element: The Piezo element is a Piezo Buzzer and called Piezo Diaphragms and Piezo Benders. It is the most popular one among all these

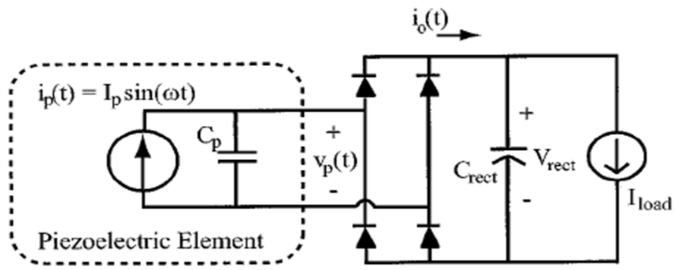

Fig. 2: Basis piezoelectric energy harvesting circuit (Ottman *et al*., 2002)

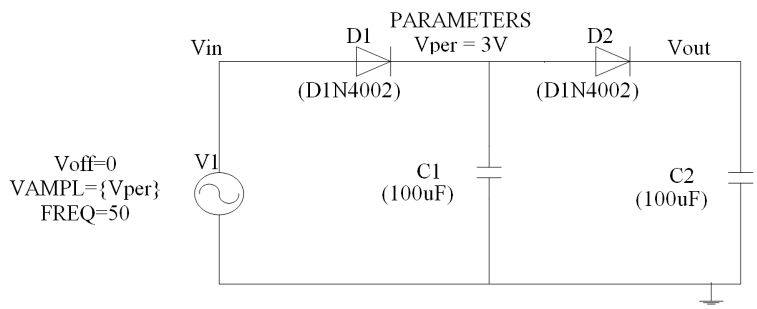

Fig. 3: Conventional passive voltage doubler rectifier

vibration-based methods because of reasonable electro-mechanical coupling coefficient, no bulky accessories (such as coil or permanent magnet). Essentially, it has offered special expertise in piezo element production from very small units for sensors, to very large units for siren. Specially formulated piezo ceramic discs are applied to a variety of base disc materials in order to suit most applications. In the general power harvesting system, there must be a transducer that harvest energy and converts it into electrical power. The abilities of a circuit comprising a rectifier and a storage capacitor are (Gautschi, 2004) tested, when a steel ball impacted a plate bonded with PZT.

The transducer can be an antenna, a piezoelectric device, a solar cell, a wind turbine and many other forms. Many mechanical vibration-based energy harvesting systems use a piezoelectric transducer as an AC power source, whose output voltage must first be rectified before being delivered to a load. This piezoelectric vibration based transducer generates a very low voltage (i.e., maximum 0.04 V) (Zhengjun and Lijie, 2010) which can be applied to the full-wave rectifier circuit that produces DC voltage without any voltage losses. A vibrating piezoelectric element can be modelled as a sinusoidal in parallel current source i_p with its internal electrode capacitance C_p = 1 uF as shown in Fig. 2 developed by Ottman *et al*. (2002). In this case, voltage source V_{in} in PSPICE was used to do the simulation. It is noted that (0.04~0.2 V) was chosen as an input voltage in PSPICE simulation, instead of piezoelectric transducer is equivalent voltage. The piezoelectric element in delivering an alternative voltage will be applied to the next module (an AC-DC power converter). The frequency and peak amplitude of the current source ω and i_p shown in Eq. (1):

$$I_p(t) = I_p \sin \omega t \tag{1}$$

Conventional passive voltage doubler diode AC-DC rectifier: The conventional voltage doubler rectifier circuit is considered to convert AC signal to DC signal for the design of the DC-DC boost converter. In operation, the sinusoidal (*V*1) voltage source is used as an input. The voltage doubler rectifier in PSPICE platform is simulated and its schematic diagram is shown in Fig. 3. It consists of a peak rectifier shaped by (*D*1) and (*C*1) and a voltage close shaped by (*D*2) and (*C*2) (Le *et al*., 2003). The voltage clamp and the peak rectifier are arranged in cascade configuration to provide a passive level shift in voltage before rectification. In the negative phase of the input, current flows through diode (*D*2) while (*D*1) is cut-off. The voltage across diode (*D*2) stays constant around its threshold voltage. At the negative peak, the voltage across capacitor (*C*1). In the positive phase of the input, current flows through diode (*D*1) while (*D*2) is in cutoff. The voltage across capacitor (*C*1) remains the same as the previous phase because it has no way to discharge. At the positive peak, the voltage across (*D*2). Since (*D*1) is conducting current to charge (*C*2), the voltage at the output is a threshold voltage below that across (*D*2).

Simulation results of conventional AC-DC rectifier: The simulation results of the voltage doubler AC-DC diode rectifier circuit is shown in Fig. 4. From this

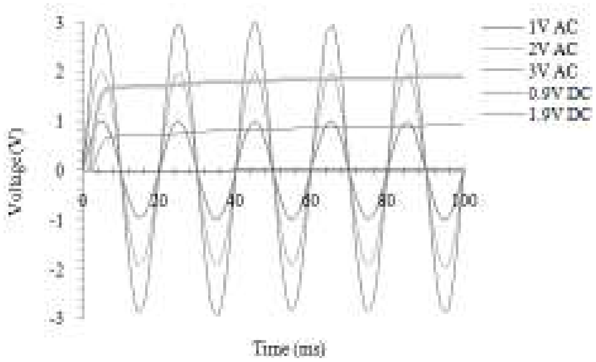

Fig. 4: Conventional voltage doubler AC-DC diode rectifier

figure, the output voltage of 0.9 and 1.9 V DC corresponding to the input voltage between 1 to 3 V AC can be observed. This simulation result shows the DC voltage with loss around 1.1 V. From this figure, it can be observed that the Diode rectifier is not suitable for the low input voltage piezoelectric energy harvester transducer due to huge voltage drop.

Development active voltage doubler thyristor AC-DC rectifier: The first stage of the development of the energy-harvesting interface circuit is the AC-DC rectifier. The AC-DC full wave rectifier circuits are developed in PSPICE platform and the schematic diagram shown in Fig. 5. The simulation results are shown in Section below. The proposed thyristor-based AC-DC voltage doubler rectifier circuit has used thyristor to convert the AC signal into DC signal for 50 Hz frequency as an input voltage generated from the piezoelectric vibration transducer at very low voltage (0.04 to 0.2 V). This level can become higher or lower depending on which range of a resonant frequency will be used to shake the piezoelectric vibration transducer. In operation, the sinusoidal (*V*1) voltage source was used as input. The development of AC-DC thyristor based rectifier circuits were used instead of diodes. The voltage pulse sources, (*V*2) and (*V*3) were used to provide the necessary gate pulses for the thyristor (*X*1) and (*X*2). This method also requires a bias resistor (*R*1) and (*R*2) which generally has resistance in the kilo ohm range (1 to 1.1 k). Although the static power dissipated from this resistor is minimal, it causes a bias voltage much less than the desired threshold voltage. The voltage drop across a diode tied is much different than one thyristor. This voltage difference is typically 0.7 V for every decade of current difference. The voltage doubler rectifier is connected with two thyristor. The input cycle is positive and thyristor (*X*1) and (*X*2) are forward-biased, thus conducting in the current direction. A voltage is developed across the resistor (*R*2) that appears similar to the positive half of the input cycle. During the half-cycle, (*X*1) and (*X*2) are reverse-biased.

The voltage doubler AC-DC rectifier circuit has been reported for its low AC voltage to convert DC voltage without loss of voltage. First, the piezoelectric vibration transducer was used as an input source. The sinusoidal (*V*1) values VOFF = 0, VAMPL = 0.04 V and FREQ = 50 Hz, as well as thyristor (*X*1) and (*X*2) were used. The voltage pulse sources were employed as a switching purpose and external voltage basing of the thyristor. The values of the (*X*1) thyristor pulses are Initial value V1 = 0, Pulsed value V2 = 3, Delay time TD = 9 m, Rise time TR = 0, Fall time TF = 0, Pulse width PW = 1 m and Period PER = 10 m. The values of the (*X*2) thyristor pulses are V1 = 0, V2 = 3, TD = 7 m, TR = 0, TF = 0, PW = 3 m and PER = 10 m. The used internal series capacitor C1 is 300 μF to filter and reduce the ripple of the output.

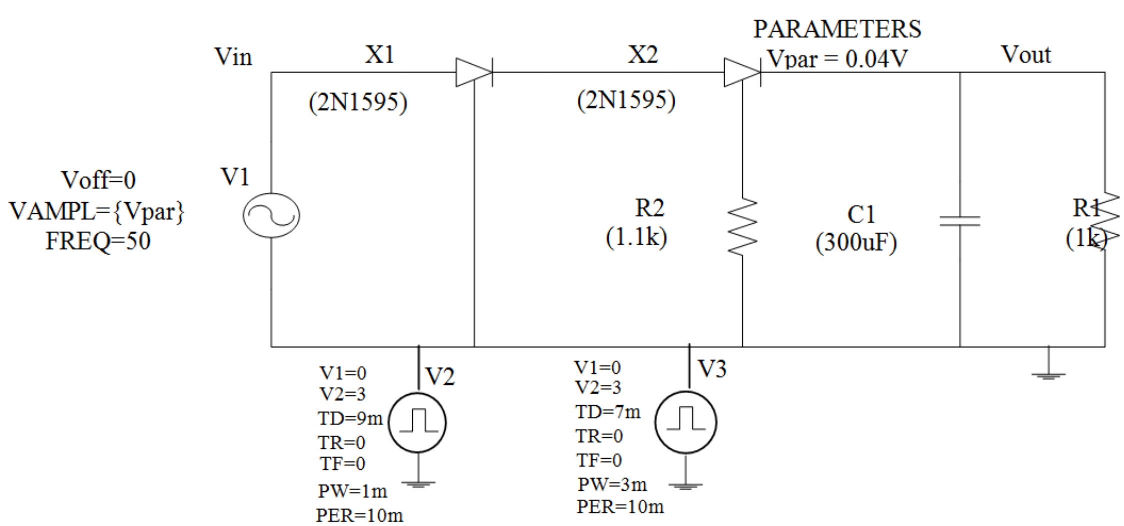

Fig. 5: Developed active voltage doubler rectifier circuit

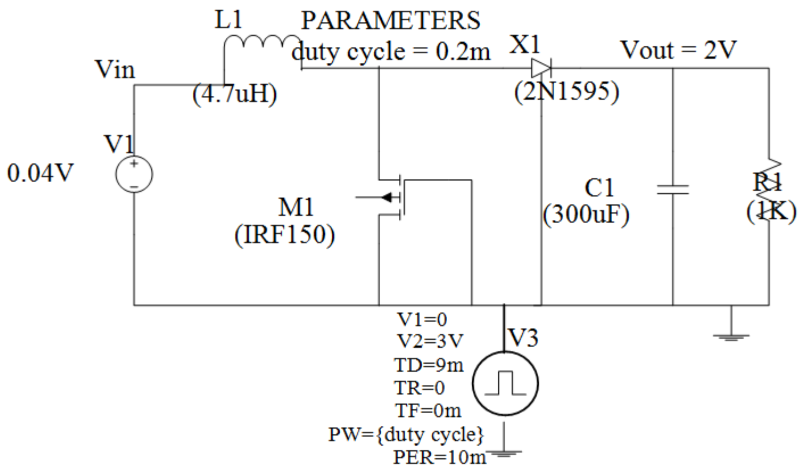

Fig. 6: Developed of the DC-DC boost converter

Temporary storage device: To design the piezoelectric energy harvesting system, capacitor plays an important role which is needed to consider for storing energy. The storage devices are such as capacitor, rechargeable batteries and super-capacitors. The rechargeable batteries store electrical energy chemically. Energy is released as electricity is activated through a chemic al reaction inside the battery cells that transfer electrons from its anode to its cathode across the electrolyte material. Recharging the battery reverses this reaction and stores electrical energy. Conventional chemistries, such as NiZn, NiMH and NiCd, offer high energy densities and good charge rates, but also feature short cycle life and adverse "memory" effects (Rodrigo, 2010). This is the common term used to replace the accurate term "Voltage Depression", which is more of a problem with incorrect charging of a battery. It occurs when the batteries are not fully discharged between charge cycles, then they remember the shortened cycle and are thus reduced in capacity (length of use per charge). The super-capacitors are alternative energy storage devices rather than traditional rechargeable batteries. Few researchers have looked into super-capacitors as energy storage devices in energy harvesting. The storage device voltage is an important factor that influences the efficiency of the piezoelectric energy harvesting system to generate the voltage to the load.

Development of the DC-DC boost converter circuit: A boost converter circuit is used to step-up a low input voltage from a power source up to the load voltage. Depending on the application and voltage available at the rectifier circuit, a boost converter is used to regulate the voltage from the output of the power conversion circuit to a stable DC voltage. The output of the piezoelectric transducer is very low and this voltage cannot be used in any application without boost up. Therefore, a boost converter needs to be developed based on an active technique to increase the voltage to use the application device. The maximum start-up voltage is 2 V of the development of DC-DC converter output while the input voltage ranges at approximately 0.04 V DC. Considering the low output voltage of the piezoelectric energy harvester, a switch-mode DC-DC converter is designed for its step-up capability and characterized by a high efficiency, up to 60% of the DC-DC converter.

In operation, the proposed circuit usually consists of resistor, inductor, MOSFET (IRF150), Thyristor/Replace of the diode (DIN4002), filter capacitors, GND_SIGNAL, PARAMETER (For defining variables and their values). As shown in the Fig. 6, the output voltage of the DC-DC converter is determined by both the input voltage V_{in} and the duty cycle (D) of the gate control signal for switch MOSFET ($M1$), which turns on and turns off the switch. In the development of the DC-DC converter, the DC input (V_{in}) = 0.04 V used is the output generated by piezoelectric stage. Considering the low output voltage of a piezoelectric energy harvester, a switch-mode DC-DC converter is designed for its step-up capability and high efficiency. For the boost converter, when the switch is turned on in time t, the input voltage would charge the load through the inductor and the inductor current increases. When the switch is turned off, the inductor current cannot be turned off immediately. The inductor current will continue to charge the load through the thyristor ($X1$) and the current value is decreased. Assuming the converter operate in the continuous conduction mode, where the inductor ($L1$) current is always higher than 0, the output voltage can be calculated to be V_{in} if apply the voltage second balance equations for the converter. Here, since the converter output voltage is determined by the duty cycle of the switch, control circuit can be designed which generates the duty cycle value from the information of the difference between current output voltage value and targeted reference voltage. In this way, the output voltage can be regulated to the reference voltage. The DC-DC switching mode converter can have very high power transfer efficiency, because the MOSFET (*M*1) is used as a switch and the conduction loss is small. The values of the thyristor (*X*1) pulses are, Initial value V1 = 0, Pulsed value V2 = 3V, Delay time TD = 9 min, Rise time TR = 0, Fall time TF = 0, Pulse width PW = 0.2 min and Period PER = 10 min. However, the converter needs the inductor (*L*1) to be implemented and the volume of the inductor is very large. An inductor (*L*1) was used which is 4.7 uH for storing the current, Resistor (*R*1) is 1 kΩ used for a better output, capacitor (*C*1) is 300 uF was used for store voltage and filtering of the output voltage to reduce ripple. Finally, the output voltage Vout (2 V) was achieved after using the DC-DC boost converter.

SIMULATION RESULTS OF DEVELOPED CIRCUIT IN PSPICE

The piezoelectric element generates the AC signal. The sinusoidal voltage have used source as an input source. The internal series capacitor has used inside the piezoelectric element. The output of the piezoelectric transducer is as shown in Fig. 7. The curve (A) observes the input voltage of the piezoelectric transducer maximum of 0.2 V AC voltage, curve (B) observes 0.14 V AC voltage, curve (C) observes 0.09 V AC voltage and curve (D) observes 0.04 V AC voltage.

The voltage doubler AC-DC rectifier circuit thyristor have used to get DC voltage with 3 stages. It can be observed from this Fig. 8 that the curve is becoming bent; initially it takes some time to reach the voltage, after 120 msec it becomes constant with 1 V DC. From this Fig. 9 it can be observed that the curve is becoming bent; initially it takes some time to reach the voltage, after 100 msec it becomes constant with 0.15 V DC. Finally, it can be observed from this Fig. 10 that the curve is becoming bent; initially it takes some time to reach the voltage, after 60 msec it becomes constant with the final output of DC voltage at different inputs of AC single (between 0.04 to 0.2 V). This phenomenon is also clear from those Figures of the different stage of rectifier output.

The "duty cycle" is selected as the parameter name from "Simulation parameters settings to get output voltage at different Pulse Width (PW). The values of PW are considered between 0.2 to 0.10 msec as well as which voltage and current are observed. The suitable value of target voltage was found for this parameter value after analysis. The start value, end value and increment are specified as shown in Fig. 11. It can be observed that the voltage increases and decreases with values of the duty cycle from this figure. However, beyond 10 msec duty cycle, the voltage near exceeds the goal of 2 V. Therefore, values for the 10 msec duty cycle are matched to achieve the expected results. Similarly, corresponding current 2 mA can be found as shown in Fig. 12. It can be observed from both these figures that the curve is becoming bent; initially it takes some time to reach the voltage, after 85 msec, it becomes constant. This phenomenon is also clear from these Figures.

Figure 13 shows the final output of the DC-DC boost converter circuit. There are two curves in the figure. Here, curve (E) shows the 0.04 V DC as an input voltage in PSPICE simulation, instead of the equivalent voltage of piezoelectric transducer circuit. Curve (F) denotes the final output of the DC-DC boost converter

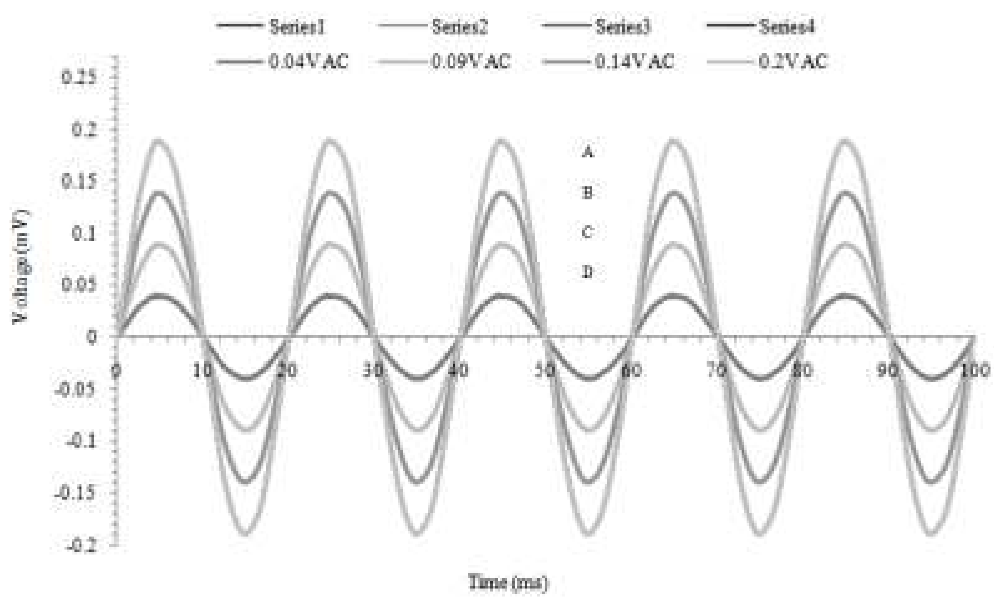

Fig. 7: Input of the piezoelectric transducer

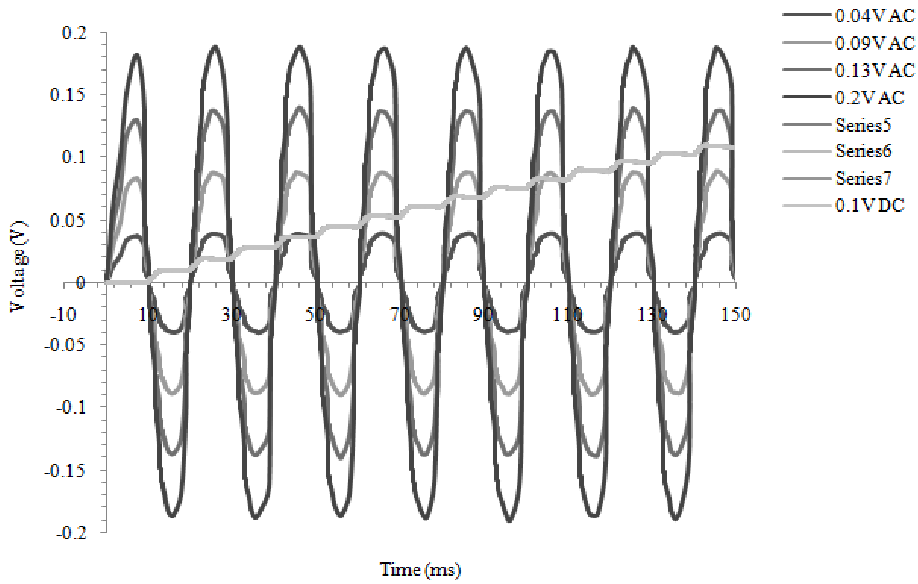

Fig. 8: First stage rectifier output voltage using thyristor

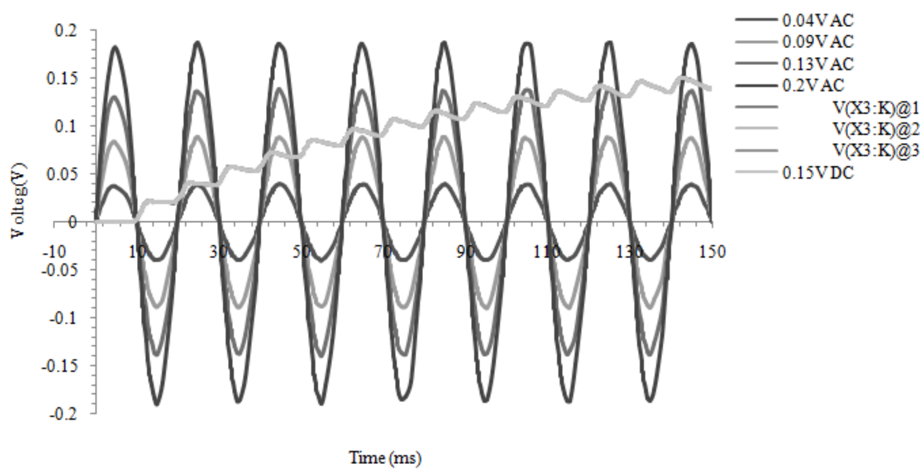

Fig. 9: Second stage rectifier output voltage using thyristor

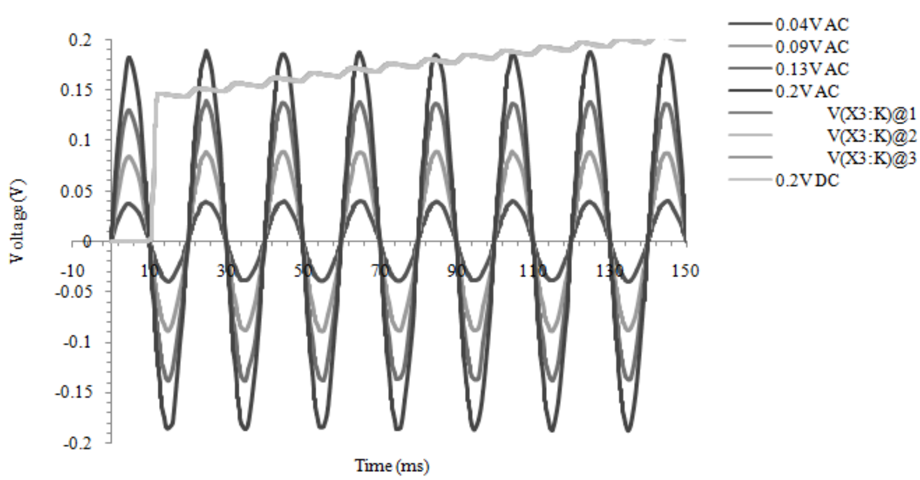

Fig. 10: Third stage rectifier output voltage using thyristor

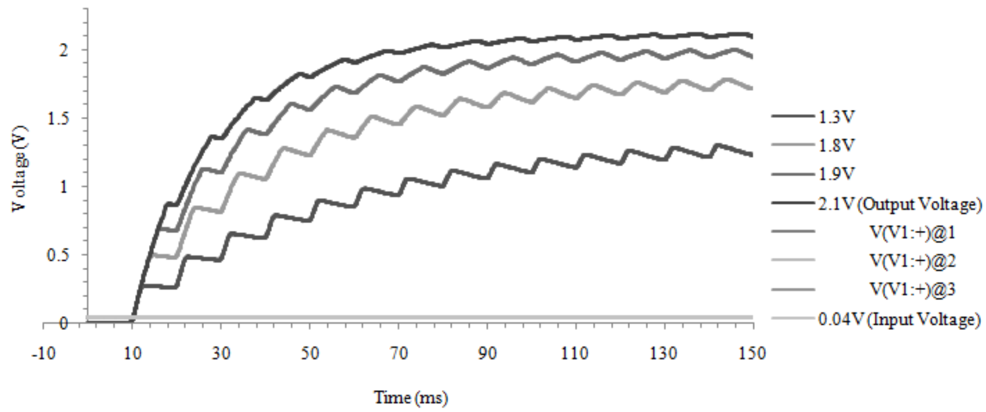

Fig. 11: Voltage waveforms with different PW

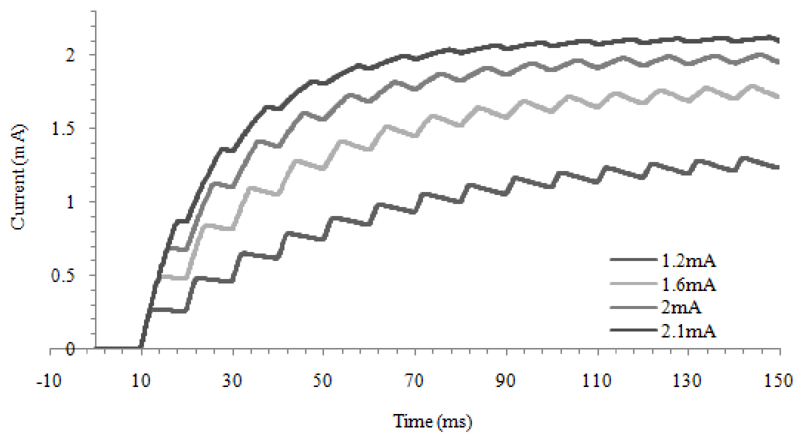

Fig. 12: Current waveforms with different PW

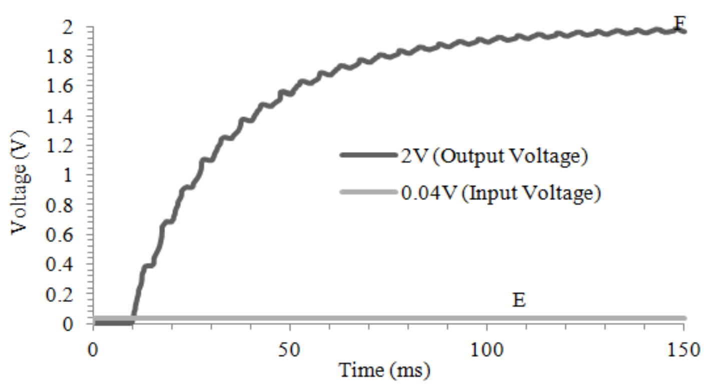

Fig. 13: Output of the DC-DC boost converter

circuit (2V). It can be observed that the curve is becoming bent; initially it takes some time to reach the voltage; after 60 m, it becomes steady.

CONCLUSION

The main focus of this study is the testing and verification of the conventional circuit, development of an energy harvesting interface circuits. The voltage doubler AC-DC rectifier circuit, DC-DC boost converter circuit have proposed and analyzed for energy harvester system (using an active technique) for autonomous devices application. The benefits of the DC-DC boost converter is enable to step-up at 2 V regulated DC voltage using 0.04 V DC piezoelectric based energy harvester equivalent voltage. Based on the results of PSPICE simulation using temporary storage device, it is able to store at 2 V as enhancement of performance of the autonomous devices. The overall efficiency of the energy harvesting interface circuit is 70%, as predicted by the simulation.

ACKNOWLEDGMENT

This study was carried out with the financial support from the Ministry of Higher Education of Malaysia under the research grant ERGS/1/2012/TK02/UKM/02/7.

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