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Designing an Integrated Voltage Tripled Circuit using Piezoelectric Vibration Generator

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Abstract: This study present designing an integrated voltage tripled circuit using piezoelectric vibration generator. Energy harvesting from the ambient source for powering micro devices have been increasing the popularity. These types of devices can be used in embedded applications or in wireless sensor networks where battery replacement is improbable. Piezo bending generator generated 1 V from force vibration has been experimentally tested. Most of the previous techniques are mainly both passive and active based energy harvesting circuits. In this research the passive technique have been proposed to design the proposed circuit. The developed voltage doubler and tripled circuit integrated with full-wave diode bridge rectifier circuitry have been designed and simulated using MATLAB/Simulink. The developed voltage doubler circuit is generated 1.5 V and the developed voltage tripled circuit is generated 2.5 V. Finally, the achievement of integrated development circuit is provided a regulate DC output voltage of 1.5 V for the input AC voltage of maximum 1 V. The overall circuit efficiency is >90% following the simulation results.

Key words: Energy harvesting, WSN, voltage tripled, low power, voltage doubler, vibration generator

INTRODUCTION

With recent growth, one of the most widely used power harvesting techniques for low power applications uses piezoelectric materials for converting mechanical energy to electrical energy. Usually, energy harvesting systems based on piezoelectric devices can be summarized into three core components: piezoelectric devices, electrical energy storage and power conversion, etc. Presently, the need of power conversion circuits for energy harvesting applications has been increased (Murugavel and Grazier, 2010). To keep up the power demand for autonomous wireless and portable devices are an important issue. The power conversion circuits need are increasing for power up and energy harvesting application. Energy harvesting techniques such as airflow power system (Fei *et al*., 2014), motion energy harvesting system (Penglin, 2006), the rmoelectric power system (Elefsiniotis *et al*., 2014; Leonov *et al*., 2007) RF power system Solar power system, piezoelectric conversion system (Scott *et al*., 2015; Hua *et al*., 2014) can be used to harvest energy from ambient environment. Different power harvesting applications, one example is WSN technology which has increased possible to be used in many areas such as automation (Christin *et al*., 2010; Chen *et al*., 2010), structural health monitoring (Park *et al*., 2008), healthcare (Ko *et al*., 2010), agriculture (Ruiz-Garcia *et al*., 2009), civil and military applications (Chalard *et al*., 2007). For example, in Wireless Sensor Network (WSN) now a days, powered by batteries. The use of batteries, numerous weaknesses including costly to replace battery as well as limitations executed by the need of suitable access to the device for battery replacement purposes, labour cost and not long life time. By scavenging ambient energy surrounding an electronic device, energy harvesting solutions have the ability to provide permanent power sources that do not require periodic as replacement of batteries, come into consideration to minimize the maintenance and the cost of operation. 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, so that the battery maintenance can be ultimately distant.

The method of energy harvesting is converting ambient energy into usable electrical energy through the use of a specific material or transduction mechanism. Different types of material occur with several conversion

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Table 1: Various vibration sources and their characteristic

Vibration sources	Peak acceleration (m/sec^2)	Peak amplitude frequency (Hz)
Kitchen blender easing	10.00	121
Clothes dryer	6.40	121
Wooden deck with people walking	1.30	385
Bread maker	1.03	121
Refrigerator	0.10	240
Drilling machine	0.93	178
Door frame just after door closes	3.00	125
Bearing test bed	10.57	200
Base of 5 HP 3-axis machine tool with 36 bed	10.00	70
Small microwave oven	2.25	121
HVAC vents in office building	0.2-1.5	60
External windows (size 2×3 ft) next to a busy street	0.70	100
Notebook computer while CD is being read	0.60	75
2nd story floor of a wood frame office building	0.20	100
A/C window unit	1.98	58
A/C compressor	2.14	59
Car engine idling	0.56	30
Car engine idling	0.52	40
Drilling machine	0.81	150
Truck engine idling	1.98	37
Lathe	1.07	60

mechanisms that can be used to harvest energy. Piezoelectric materials have received the most attention for obtaining electric energy from the surrounding environment for their ability to directly convert vibrations into electrical energy (Christin *et al*., 2010). Among the various modes of energy harvesting, vibration energy harvesting is the most versatile technique developed in the literature (Guan and Liao, 2008). Various vibration sources and their characteristic as shown in Table 1 (Leland *et al*., 2005). The 3 main mechanisms of vibration to electrical energy conversion exist including electrostatic, electromagnetic and piezoelectric transducer. In general transducer is the system of energy harvesting is described that harvest energy from ambient source and converts it into usable electric energy. The transducer can be an antenna, a piezoelectric device, a solar cell, a fuel cell, a wind turbine and many others forms. The research motivation in this field is due to the reduced power requirement of small electronic components such as the wireless sensor networks used in passive and active monitoring applications. Advances in low power micro devices design along with the low duty cycles of wireless sensors have reduced power requirements of 100~1000 sec of μW in MICA with projections into 10s of μW. Such trend enhances the feasibility of energy harvesting techniques. Figure 1 illustrates a summary on power consumption of common wireless sensor nodes at different operating modes where the data is obtained from. The maximum power for most wireless nodes is typically 200 mW which strongly depends on sampling rate, transmission range and transmission speed of the sensor node.

From an electrical engineering point of view, the alternating voltage output should be converted to a stable

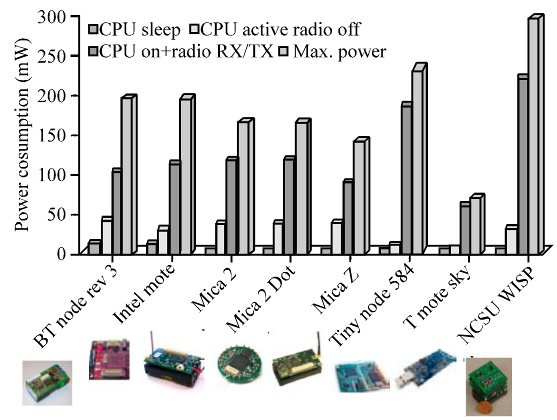

Fig. 1: Power consumption of common wireless sensor nodes at different modes

rectified voltage through a rectifier bridge and a smoothing capacitor (which constitute an AC-DC converter) for charging a small battery or a capacitor by using the harvested energy. Often a 2nd stage (DC-DC converter) is employed to regulate the voltage output of the rectifier so that the power transfer to the storage device can be maximized. The ultimate goal in this research field is to power such small electronic devices by using the vibrational energy available in their environment.

Development of the energy harvester system circuit using piezo bending generator: This study presents the preliminary study on piezoelectric energy harvesting such as PBG, voltage doubler, voltage tripled circuits, full wave AC-DC bridge rectifier and temporary storage device. The proposed block diagram of piezoelectric energy harvester system is shown in Fig. 2. All these features are demonstrated through selective block diagram.

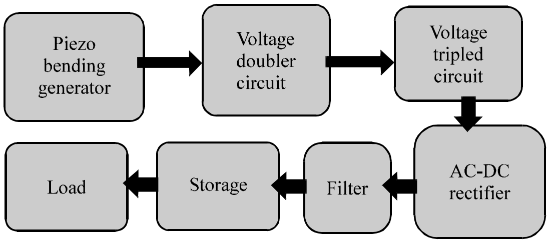

Fig. 2: Poposed block diagram of piezoelectric energy harvester system

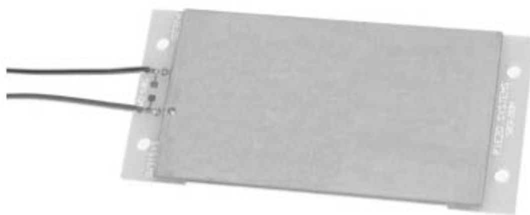

Fig. 3: Prototype of the piezoelectric bending generator

Table 2: Piezoelectric bending generator parameters

Parameters	Piezo bending generator	Units
Piezo material	5A4	E
Weight	10.4	g
Stiffness	1.9×102	N/m
Capacitance	232	nF
Rated tip deflection	±2.6	(mm_{peak})
Max. rated frequency	52	Hz
Open circuit voltage	±20.9	Vpeak
Closed circuit current	±57	µApeak/Hz)
Rated output power	7.1	mWrms

Vibration piezoelectric bending generator: Single PBG has been tested with the energy harvesting power conversion circuits. The prototype of a PBG is shown in Fig. 3. The parameters values of PBG are summaries shown in Table 2. The energy harvesting bender one side is flexed and another side free to move. When a piezoceramic transducer is stressed mechanically by a force vibration its electrodes receive a charge that tends to counteract the imposed strain. This charge may be collected, stored and delivered to power electrical circuits.

Voltage tripled circuit: A voltage tripled is an electrical circuit that converts AC electrical power from a lower voltage, typically using capacitors and diodes. Connecting diode in a predetermined manner an AC signal can be doubled, tripled and even quadrupled. The voltage tripled rectifier structure is considered in this study to multiply output voltage of the single PBG. Circuit designs results are presented 5. The proposed voltage doubler and tripled circuit as shown in Fig. 4-5.

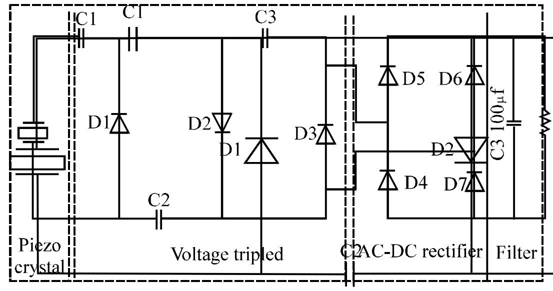

Fig. 4: Proposed voltage doubler circuit

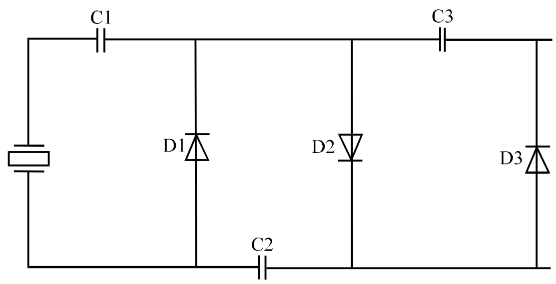

Fig. 5: Proposed voltage tripled circuit

AC-DC full wave bridge rectifier: Many vibration-based energy harvesting systems use a piezoelectric transducer as an AC source. It generates voltage which must first be rectified before it can be used by a load. Typically, the energy from a piezoelectric transducer that has two electrodes is rectified using a full-wave diode bridge rectifier which requires a significant voltage drop between input and output, decreasing the rectifier voltage efficiency. The extract piezoelectric strain energy will produce an AC voltage as an electrical energy. However, most of the low power electronic device nowadays only uses a low DC voltage. Therefore, the AC output voltage needs to rectify and convert it to the usable DC voltage to supply to the load circuit which is contented with electronic devices.

The 3rd stage needed in an energy harvesting circuit is the AC-DC rectifier. A diode bridge rectifier is generally used as the AC-DC rectifier that includes four Schottky diodes and capacitor connected to the cathode of the diodes to filter a rectified voltage output. As developed by Ottman *et al*. (2007), there exists an optimal rectifier voltage Vrect_opt to harvest the energy for maximum ower. The optimal rectifier voltage Vrect_opt is one-half the peak open-circuit voltage V_{oc} by Eq. 1:

$$V_{rect\_opt} = \frac{V_{oc}}{2} = \frac{I_p}{2\omega C_p} \quad (1)$$

However, since the diode-bridge rectifier circuit can also follow a resistive load while the internal impedance of a piezoelectric device is essentially capacitive the impedance matching condition cannot be satisfied and so generally, the power harvesting ability of the passive technique is used in this research.

The available semiconductor rectifiers fall short of ideal behavior in several respects the most serious shortcoming in the application of energy harvesting, where the AC frequency is low is the drop in voltage across the device when conducting in the forward direction. This subtracts from the voltage generated by the harvester and it is therefore desirable to use a device having the lowest forward drop. Discounting germanium devices (forward drop~0.25 V) which are not widely available with an appropriate current rating, silicon or Schottky diodes could be used. Schottky diodes need a forward voltage of 0.4 instead 0.7 V to operate within a circuit. In the bridge configuration, two diodes conduct at any one time hence even with Schottkty diodes of a substantial amount of the harvester output voltage can be dropped over the diode with the consequent losses. This problem is not so prevalent in piezoelectric based harvesters since the output voltage is typically much higher (Priya, 2007).

In this researche, the full-wave diode bridge AC-DC rectifier circuit integrated with the PBG and voltage tripled circuit is shown in Fig. 6. The piezo generator generate very low input voltage which diode-bridge full-wave rectifier do not work properly, i.e., the forward voltage of iode 0.7 V potential is higher than the input. To eliminate this problem the voltage tripled circuit has been proposed in this study before rectifier to design the energy harvester system.

Filter: Generally the piezo bending generator is generate AC voltage with ripple. AC-DC full-wave rectifier has been used to produce DC signal. To storage the voltage need smooth DC voltage for drive load but to get smooth DC voltage need to apply RC filter.

Temporary storage device: Generally, capacitors are considered as purpose of storage on the piezoelectric energy harvesting system. Others energy storage devices are such as rechargeable batteries and super-capacitors. Presently, some researchers are proposed super-capacitors as alternative energy storage devices other than traditional electrolytic capacitors and rechargeable batteries. The energy density of super-capacitors is 10-100 times higher than that of traditional electrolytic capacitors.

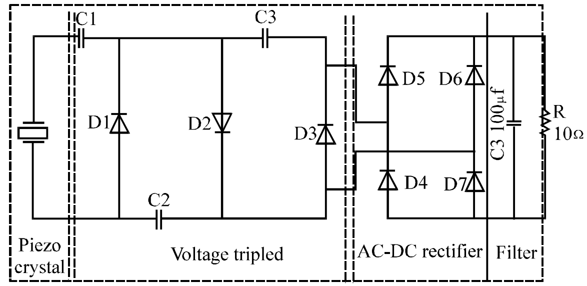

Fig. 6: Circuit diagram of the developed energy harvester system with the Piezoelectric Transducer, voltage tripled, AC-DC rectifier and filter

MATERIALS AND METHODS

Experimentally setup and tested the piezo bending generator: Hardware architecture is the representation of an electronic system, process and control for implementing the design for such a prototype system. It is generally a part of an integrated system consisting of the circuit information and software for designing device architecture. The hardware implementation is one of the important roles to test/verify the circuit functionality in proper operation.

In the following sections have described in details about the simulation on MATLAB/simulink based on the hardware steps, procedure and results. The developed schematic circuits diagram (using passive technique) for energy harvester already is shown in Fig. 6. The piezo bending generator (i.e., vibration transducer) has been used as an input source in this experiment is show in Fig. 7. The experimental results of the PBG are shown in Fig. 7 and 8. Figure 7 represents the measured input voltage of V_{pp} 1 V with frequency of 100Hz. The resonance frequency peak 100Hz is shown in Fig. 9. The PBG voltage is applied as an input of the next section (i.e., voltage doubler circuit, voltage tripled circuit and AC-DC rectifier circuit).

Development of the integrated energy-harvester system in MATLAB/simulink: This study presents the proposed symmetric of fully energy harvester system with piezoelectric transducers, voltage doubler circuit, voltage tripled circuit, AC-DC rectifier, filter and using a temporary storage device as shown in Fig. 9. In the general power harvesting system, there must be a transducer that harvests energy and then converts it into electrical power.

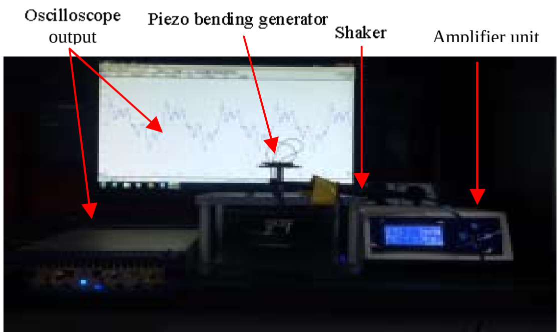

Fig. 7: Experimental setup of the energy harvester piezo bending generator

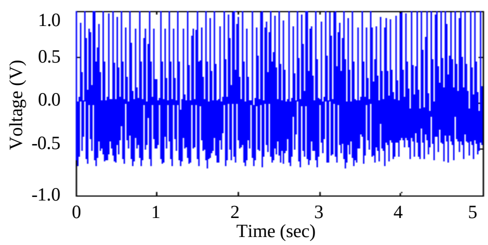

Fig. 8: Experimental voltage output of piezo bending generator

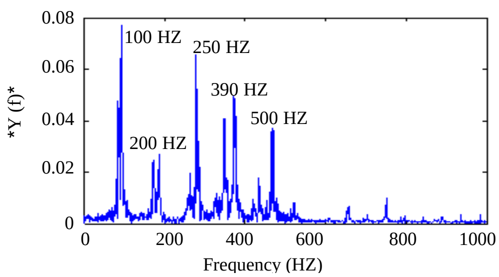

Fig. 9: Peak resonance frequency of piezo bending generator

The transducer can be mechanical vibration-based energy harvesting system use piezoelectric transducer as an AC power source whose output voltage must first be rectified before being delivered to a load. This generated voltage of the single piezoelectric vibration transducer is very low 1 V. So, the passive based full-wave diode bridge rectifier is not enough to convert AC-DC because of the forwarding voltage of diode minimum 1 V. In this study, a voltage tripled circuit has been proposed to recovery this problem.

RESULTS AND DISCUSSION

Simulation results of the fully energy harvester system in MATLAB/Simulink: The sinusoidal input voltages

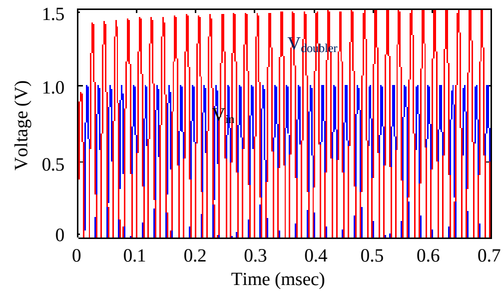

Fig. 10: AC input voltage, output voltages from doubler simulated by Simulink

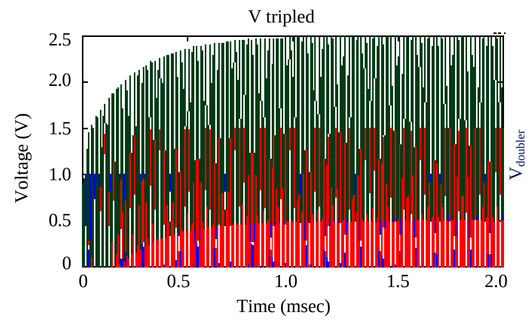

Fig. 11: AC input voltage, output voltages from doubler and tripled simulated by Simulink

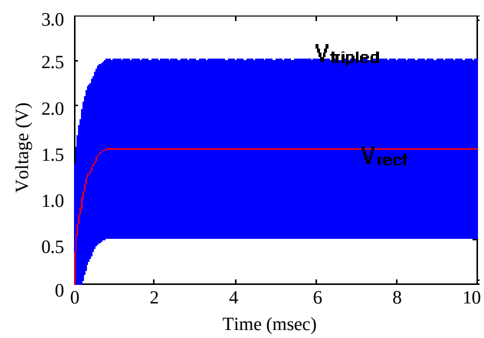

Fig. 12: Output voltage of the voltage integrated circuit

PBG produce 1 V with frequency of 100 Hz have been implemented and the output results shown in Fig. 3. Using simulink the output voltages of the doubler and tripled circuits have been shown in Fig. 10 and 11. 100 μF capacitors and Schottky diodes are used in the circuits. Since the forward voltage drop of each diode is considered in simulink, vdoubler and vtripled approach 1.5 and 2.5V, respectively, from the output voltage of the piezo bending generator maximum 1 V AC voltage with 100 Hz frequency.

The integrated circuit output is shown in Fig. 12. According to the Fig. 12, two curves are shown, Vtripled output 2.5 V DC and Vrect of the AC-DC full-wave bridge rectified output 1.5 V DC. The curve shows the horizontal voltage range between 0-3 V. The times range of the voltage are between 0-10 m sec. From Fig. 12, it can be observed that the curve is becoming bent; initially, it takes some time to reach the voltage; after 1 m sec, it becomes steady. Finally, the integrated energy harvester circuit is produced 1.5 V with stable voltage.

CONCLUSION

The main focus of this research is the designing an integrated voltage tripled circuit using piezoelectric vibration generator. The fully integrated energy harvesting circuit (i.e., voltage doubler, voltage tripled and AC-DC full-wave diode bridge rectifier circuit) has been designed using MATLAB/Simulink simulation and piezo bending generator as an input voltage source that generated maximum 1 V which experimentally tested in hardware level. The developed circuit have proposed and analyzed an energy harvester system (using a passive technique) for micro-devices application. The developed circuits in MATLAB/simulink simulation is generated the maximum voltage of 1.5 V for an input voltages 1 V. The overall circuit efficiency is >90%, followed by the simulation results.

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