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Efficiency Evaluation of a MOSFET bridge rectifier for Powering LEDs using Piezo-electric Energy Harvesting Systems

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Original scientific paper

Harvesting energy from the renewable energy sources plays a very important role in recent days. Researchers are using various methods to capture the energy for different sources. One of the most prominent methods of energy harvesting from vibrations is by using piezo-electric material. Piezo-electric vibration harvesting is smart mainly due to the simplicity of piezoelectric transduction and the piezoelectric systems can be easily implemented into a wide variety of applications. Due to wide range of AC output voltage and low power, the piezo-electric generator cannot directly prop up the AC or DC electrical appliances. Hence in the majority applications the AC signal created by this generator needs to be rectified. In this paper a new highly efficient MOSFET full bridge AC to DC converter for piezoelectric energy harvesting is planned, which enhances the power extracted from the piezo-electric crystal. The proposed AC to DC converter reduces the voltage drop along the conduction path and thereby increases the power extraction and conversion capability. The proposed circuit is replicated in PSpice software package and then in the experimental setup. The performance is evaluated and compared.

Key words: LED lighting, Piezoelectric vibration energy harvesting, Power converter, Renewable energy

Procjena učinkovitosti mosnog MOSFET ispravljača za napajanje LED rasvjete korištenjem piezoelektričkog sustava za prikupljanje energije. Prikupljanje energije iz obnovljivih izvora odigralo je važnu ulogu u recentnoj povijesti. Istraživači danas koriste različite metode za prikupljanje različitih oblika energije. Jedna je od najistaknutijih metoda prikupljanje energije vibracijama korištenjem piezoelektričkih materijala. Ovaj način ističe se jednostavnošću piezoelektrične vodljivosti, a sustavi se mogu jednostavno implementirati u široki opseg primjena. Zbog širokog raspona AC izlaznog napona i male snage, piezoelektrički generator ne može se direktno spojiti na AC ili DC električne uređaje. Stoga je za većinu aplikacija AC signal ovakvog generatora potrebno ispraviti. U radu se prikazuje planiranje nove visoko-efikasne topologije punog mosnog spoja MOSFET-a AC/DC pretvarača za piezoelektričko prikupljanje energije, koje pojačava prikupljenu energiju iz piezoelektričnog kristala. Predloženi AC/DC pretvarač smanjuje propad napona duž puta vođenja i time povećava prikupljanje energije i sposobnost konverzije. Predloženi sklop izrađen je u PSpice programskom paketu, a zatim na eksperimentalnom postavu. Svojstva sklopa procijenjena su i uspoređena.

Ključne riječi: LED rasvjeta, piezoelektričko vibracijsko prikupljanje energije, pretvarač snage, obnovljivi izvori

1 INTRODUCTION

The main problem we all face currently in the world is the over consumption of our energy resources, if we go at this pace then our future cohort will have a lack of supply of energy resources. Harvesting energy is a new groundbreaking technology and this paper deals with such harvesting of electrical energy through a piezoelectric element which is excited mechanically. The element acts similar to source which provides electrical power with only difference being that it is driven by a reflex force and the source impedance is capacitive in nature. The mechanical force itself will be of irregular amplitude.

Mostly the power generated from the piezoelectric transducer is in the order of milliwatts and fluctuating, which cannot be directly applied to the load and it has to be rectified [1, 2]. This ensures the necessity of an AC to DC converter, which is capable of extracting more power from the transducer. Traditionally used diode bridge AC to DC converter suffers from forward voltage drop across the diodes which constitute the major part of conduction losses [3, 4]. So that the power extracted from the transducer is reduced. The comparator based active AC to DC converter [5] has leakage and oscillation problems due to DC offset of the comparator which reduces the efficiency of power extraction from the transducer. An operational amplifier based half bridge AC to DC converter is described in [6] which overcomes the DC offset problem but it has low output power due to poor efficiency. This paper describes an approach of harvesting electrical energy from a mechanically excited piezoelectric element. An efficient MOSFET bridge AC to DC converter is proposed which overcomes the limitations of conventional AC to DC converters.

2 PIEZO-ELECTRIC ENERGY HARVESTING

Figure 1 shows the schematic representation of the concept of piezoelectric energy harvesting system of the material. The alternating voltage output from the piezoelectric transducer should be converted to a stable rectified voltage through an AC to DC converter and a smoothing capacitor which constitute an AC–DC converter for charging a small battery or a capacitor by using the harvested energy. Habitually a second stage DC–DC converter is employed to regulate the voltage output of the AC to DC converter, so that the power transfer to the storage device can be maximized.

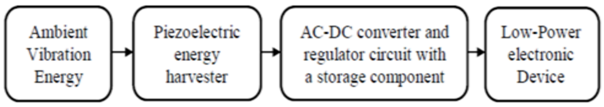


Fig. 1. Schematic Representation of Piezoelectric Energy Harvesting

3 MODELLING OF PIEZOELECTRIC CRYSTAL

Figure 2 shows the equivalent circuit of a piezoelectric device which is driving a load. The piezoelectric crystal can be designed as a sinusoidal current source I_{piezo} in parallel with a capacitor C_{piezo} and internal resistance R_{piezo} [7]. The power output of the piezoelectric transducer is low power AC which cannot be directly applied to load so that it has to be rectified. This ensures the necessity for an AC to DC converter which is capable of extracting maximum power from the transducers.

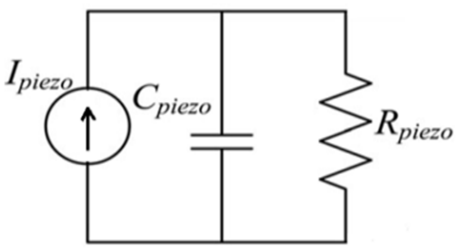


Fig. 2. Equivalent Circuit of a Piezoelectric Crystal

However, the performance of a piezoelectric micro generator strongly depends on the electromechanical coupling that is related in particular to the piezoelectric material properties and quantity. The electric field across the material affects its technicalities, and the pressure in the material modifies its dielectric properties. The constitutive equations of piezoelectric is defined as follows:

$$D = dT + \varepsilon E,$$

$$S = \frac{T}{Y} + dE,$$

where D-electrical displacement, d-piezoelectric strain coefficient, T-mechanical stress, ε-dielectric constant, E-electric field, S-mechanical strain, Y-Young's modulus. A vibrating piezoelectric device generates an AC voltage while electrochemical batteries require a DC voltage, hence the first juncture needed in an energy harvesting circuit is an AC-DC converter connected to the output of the piezoelectric device. So an AC to DC converter which is capable of extracting maximum power from the piezoelectric transducer is necessary.

4 BLOCK DIAGRAM OF THE PROPOSED SYSTEM

Figure 3 shows the block diagram of the proposed system. The output from the piezoelectric crystal is an AC signal. The AC signal cannot be directly applied to the load because of the wide frequency range. So the output from the transducer is rectified by the proposed MOSFET Bridge AC to DC converter.

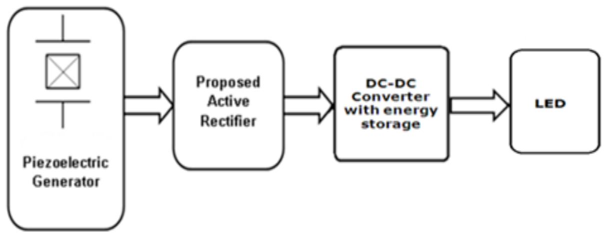


Fig. 3. Block Diagram of the proposed system

The MOSFET bridge AC to DC converter is capable of extracting more power from the transducer by reducing the conduction losses. The rectified DC voltage is regulated by a DC-DC converter and also it filter out the ripples. The DC-DC converter may be buck or boost converter depending on the load. If the load requires high voltage then it can be stepped up by using boost converter. When the load requires low voltage, the buck converter is used to step down the voltage. The regulated DC voltage is then stored in battery. The stored energy is then used for supplying electronic load such as LED lighting, battery chargers, Portable electronics, Wireless sensors etc.

5 PROPOSED MOSFET BRIDGE AC TO DC CONVERTER

In this paper a MOSFET bridge AC to DC converter with switch control is proposed which has the capability of extracting more power from the transducer. MOSFET Bridge AC to DC converter is one which replaces the passive diodes in the conventional AC to DC converter [8] with an operational amplifier-controlled counterpart and a switch is added across the transducer. The proposed MOSFET Bridge AC to DC converter reduces the conduction drop, so that the maximum power is extracted from the transducer [9].This leads to better conversion capability and power extraction. Fig.4 shows the circuit diagram of a MOSFET bridge AC to DC converter with switch control. It consists of four MOSFET based rectifying diodes in which two of them are PMOS transistors and other two are NMOS transistors. The upper group of the bridge constitutes of PMOS transistors and lower group is of NMOS transistors. The two PMOS transistors are cross-coupled with each other and the two NMOS transistors are controlled by operational amplifier with an offset voltage V_{OS}. The input is a sinusoidal current source given by $i_P(t) = I_P \sin(2\pi f_P t)$, where I_P is the amplitude of current and f_P is the excitation frequency[10]. This current source is in parallel with a capacitor C_P and an internal resistor R_P. A switch SW is also connected across the piezoelectric source. The Capacitor C_L is used to store the harvested energy and R_L is the load resistor.

During the positive half cycle the steady state operation of the circuit is classified into three operating modes [12].

5.1 Mode I Operation

Figure 5 shows the equivalent circuit of mode I operation. During this mode the current I_P is used to charge C_P only. In this mode, since the current I_P is very small the source voltage V_{PN} is less than the threshold voltage V_{THP} of the PMOS transistor M_{P1}, $0 < V_{PN} < |V_{THP}|$,

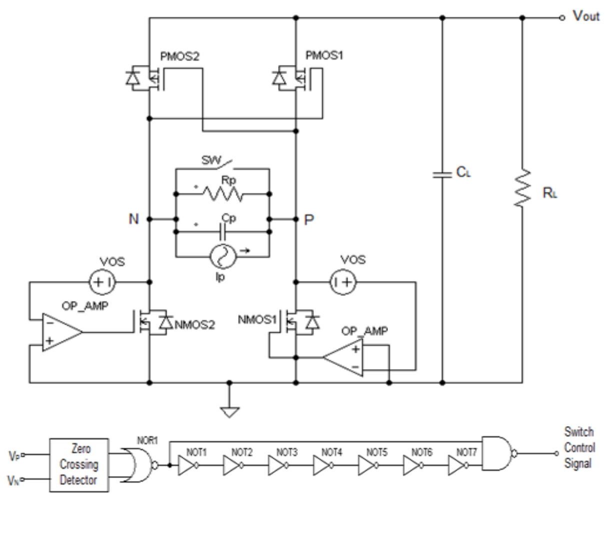


Fig. 4. MOSFET bridge AC to DC converter with Switch Control

so that M_{P1} is in OFF state. Also the Source voltage at node N, V_N is greater than zero; $V_N > 0$, the NMOS transistor M_{N2} is also in OFF state. So that the current flows only through C_P and not through the load capacitor C_L.

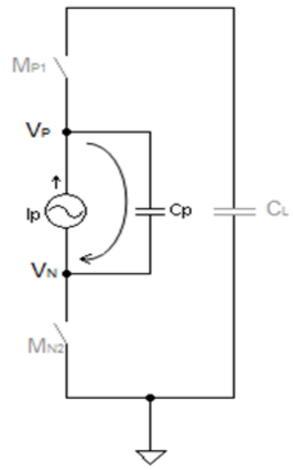


Fig. 5. Equivalent Circuit of Mode I Operation

5.2 Mode II Operation

In this mode the current I_P increases further so that the source voltage V_{PN} becomes greater than or equal to the threshold voltage of $M_{P1}, V_{PN} \geq |V_{THP}|$, so that M_{P1} turns ON. Figure 6 shows the equivalent circuit of mode II operation. Since M_{P1} is on, the node P is shorted to the output of the AC to DC converter. However the voltage at node N, V_N is still greater than zero, M_{N2} is in OFF state. So that the current I_P keeps on flowing into C_P,which causes V_{PN} to increase further. In this mode also current will not flow into the load capacitor C_L because M_{N2} is in OFF state.

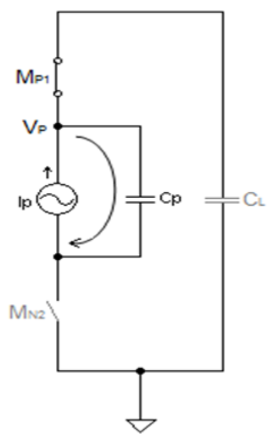


Fig. 6. Equivalent Circuit of Mode II Operation

5.3 Mode III Operation

In this mode increase in V_{PN} leads to decrease in V_N. When V_N becomes lesser than or equal to the offset voltage V_{OS} of the operational amplifier, $V_N \leq V_{OS}$ the output of the op-amp is switched to high and thus M_{N2} is turned on. Figure 7 shows the equivalent circuit of mode III operation. Here we can see both the MOSFETs M_{P1} and $M_{N2}$are ON. This causes the current to flow through the load capacitor C_L. The value of C_L is much larger than that of C_p so most of the current flows through C_L.

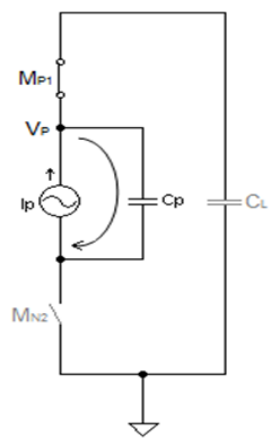


Fig. 7. Equivalent Circuit of Mode III Operation

As I_P starts reducing and when it reaches zero, the switch SW across the transducer closes and discharges the capacitor C_P for an instant of time by shorting the nodes P and N so that V_{PN} becomes zero [6]. During this period, both M_{P1} and M_{N2} are in OFF state. The switch SW opens when the capacitor C_P has been discharged and thus the positive half cycle ends. The use of switch reduces the waste of current I_P to discharge C_P before the next half cycle starts so that more amount of energy is transferred to the output. The delay for switch control is achieved by the combination of NOT gates. The input to the delay circuit is provided by detecting the zero crossing of the P and N node voltages [9]. Similarly during the negative half cycle the same modes of operation occur but here M_{P2} and M_{N1} are involved. So that during each half cycle of operation one transistor from upper half and other from lower half conducts. Thus the input AC power is rectified to DC output at the load terminals and is stored in the load capacitor C_L.

6 SIMULATION ANALYSIS OF AC-DC CONVERTERS

The performance characteristics of three different configurations of AC-DC converters such as Conventional Diode Bridge AC to DC converter, MOSFET Bridge AC to DC converter and MOSFET bridge AC to DC converter with Switch Control are performed using PSpice Schematics software package.

6.1 Diode Bridge AC to DC converter

Figure 8 shows the simulated circuit of diode bridge AC to DC converter. Here a cantilever based PZT crystal is considered as the source. The parameters used for simulation are input current is 200μA, input capacitance, C_1 is 25nF, input resistance, R_1 is 30kΩ, load capacitor is 10μF and load resistance is 24kΩ.

Figure 9 shows the input current and voltage waveforms of diode bridge AC to DC converter. The input power is given by $VI\cos\varphi$ and is found to be 158.48 μW.

Figure 10 shows the output voltage and current waveforms of diode bridge AC to DC converter it is found that the output power is given by $V \times I$ and is equal to 60.36μW. So that the efficiency of the AC to DC converter is found to be only 38.08%.The efficiency is less due to the forward conduction drop in the diodes [10].

6.2 MOSFET Bridge AC to DC converter

Figure 11 shows the MOSFET bridge AC to DC converter in which the diodes are replaced by PMOS and

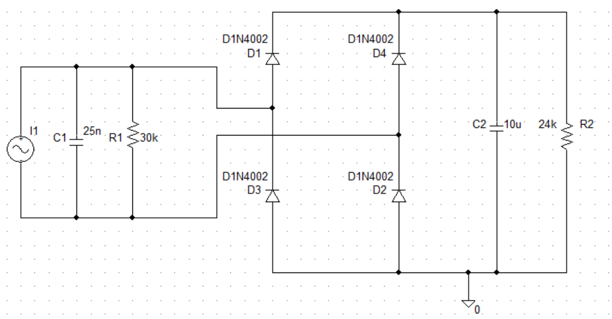


Fig. 8. Diode Bridge AC to DC converter

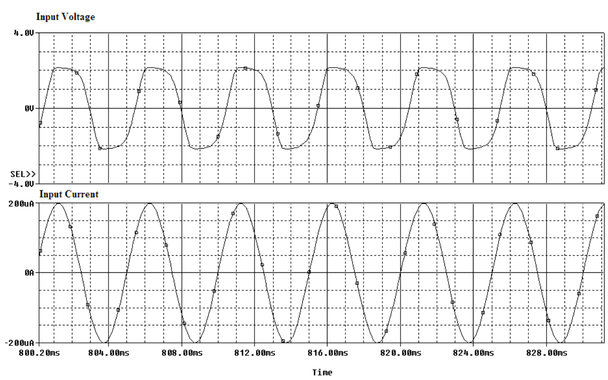


Fig. 9. Input Current and Voltage Waveforms of Diode Bridge AC to DC converter

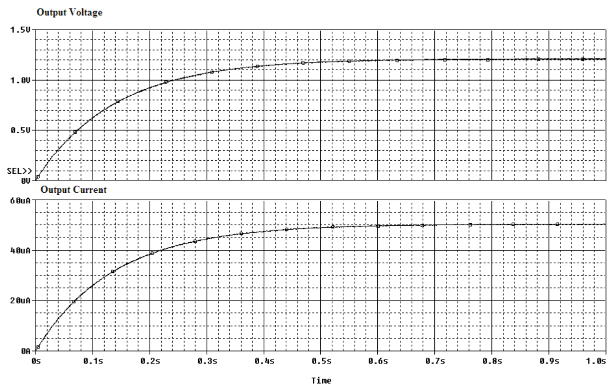


Fig. 10. Output Voltage and Current Waveforms of Diode Bridge AC to DC converter

NMOS transistors. The Upper two PMOS are cross coupled with each other to reduce the conduction losses and the lower two NMOS transistors are controlled by operational amplifiers. Whenever the output of op-amp is high the NMOS transistors are switched ON.

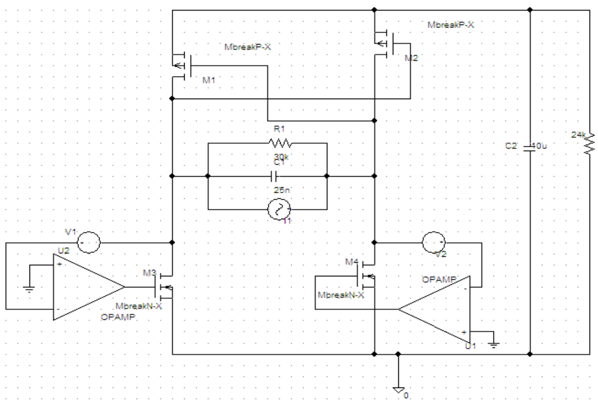
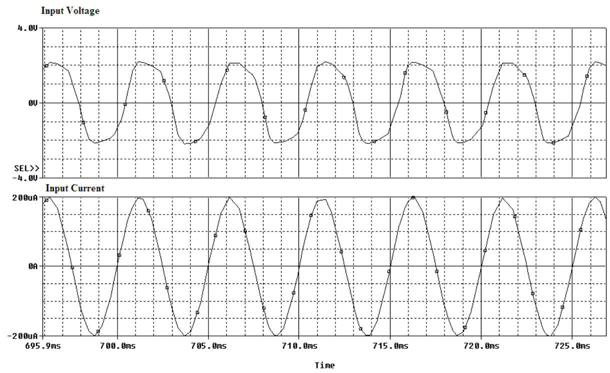


Fig. 11. MOSFET bridge AC to DC converter

Fig. 12. Input Voltage and Current Waveforms of MOSFET bridge AC to DC converter



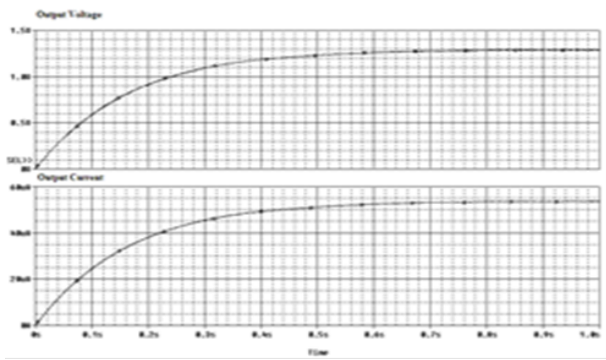


Fig. 13. Output Voltage and Current Waveforms of MOSFET bridge AC to DC converter

Figure 12 shows the input current and voltage waveforms of MOSFET Bridge AC to DC converter. Here the input power is found to be 151.9μW.

Figure 13 shows the output voltage and current waveforms of MOSFET Bridge AC to DC converter. The output power is found to be 68.14μW.So that the efficiency is found to be 44.8%.This shows some improvement over the diode bridge due to the reduction in conduction losses [11].

6.3 MOSFET bridge AC to DC converter with Switch Control

Figure 14 shows the MOSFET Bridge AC to DC converter with switch control. Here a switch is connected across the source which turns ON whenever the input current reaches zero and discharges the source capacitor. The delay for Switch operation is provided by NOT gates.

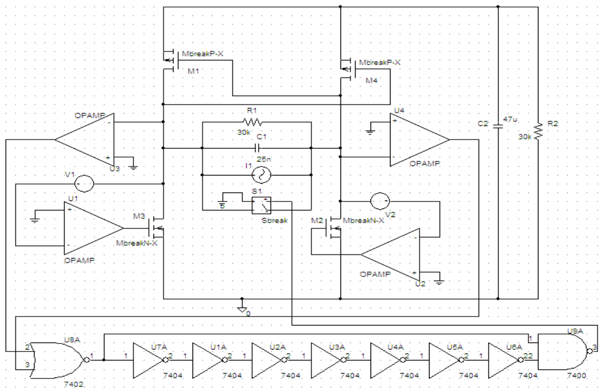


Fig. 14. MOSFET Bridge AC to DC converter with Switch Control

Figure 15 shows the input voltage and current waveforms of MOSFET Bridge AC to DC converter with switch control. From the waveform the input power is found to be 225μW.

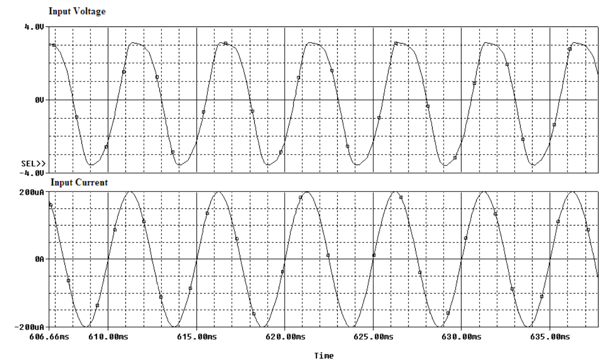


Fig. 15. Input Voltage and Current Waveforms of MOSFET Bridge AC to DC converter with Switch Control

Figure 16 shows the output voltage and current waveforms of MOSFET Bridge AC to DC converter with switch control. Here the output power is found to be 210μW.

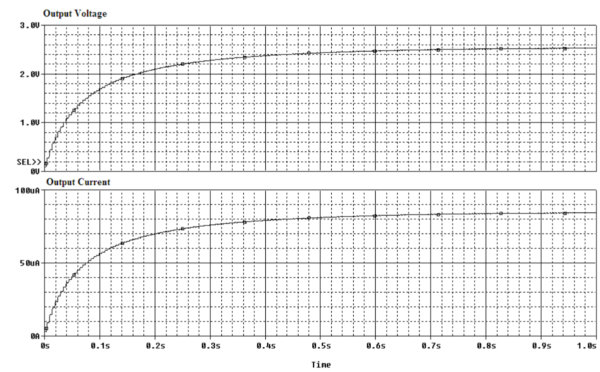


Fig. 16. Output Voltage and Current Waveforms of MOSFET Bridge AC to DC converter with Switch Control

Here the wastage of current during the discharge of source capacitor is reduced by the switch control. Thus the switch saves the power by limiting the current that circulates in the source side and supplies more current to the load. So that the power extracted from the transducer is increased. The efficiency of power extraction has increased to 93.3%.

Table I shows the simulation analysis of various AC to DC converters used for harvesting energy from piezoelectric transducer. The proposed MOSFET Bridge AC to DC converter with switch control shows a maximum efficiency of 93.3%. So that it can be a better choice for harvesting piezoelectric energy.

Table 1. Performance Evaluation of Various AC to DC converters

Parameters	Diode Bridge	MOSFET Bridge AC to DC converter Without Switch	MOSFET Bridge AC to DC converter with Switch
Input Voltage	2.18V	2.09V	3.1V
Input Current	200µA	200µA	200µA
Output Voltage	1.2V	1.28V	2.5V
Output Current	50.28µA	53.24µA	84µA
Input Power	158.48µW	151.9µW	225µW
Output Power	60.36µW	68.14µW	210µW
Efficiency	38.08%	44.8%	93.3%

7 EXPERIMENTAL ANALYSIS OF AC-DC CONVERTERS

To validate the simulated results obtained, it is necessary to verify their performance with an experimental analysis. The first stage of the experimental setup is an energy harvester which consists of an iron ball attached onto an ordinary piezoelectric transducer. The mass bonded weighs 56 grams and the transducer has the following dimensions: metal diameter (d_m=40mm), metal thickness (h_m=0.25mm), piezo diameter (d_p=23mm) and piezo thickness (h_p=0.34mm). The mechanical vibrations are generated by actuating electromagnetic shaker with a sinusoidal voltage. Figure 17 presents the setup of electromagnetic shaker and piezo electric energy harvester. The $V-I$ characteristics of piezo electric device is measured using a digital storage oscilloscope. The frequency of the output voltage obtained is same as the frequency of vibrations. Also the magnitude of the output voltage is proportional to the magnitude of the vibrations.

This energy generated from the first stage hardware setup is given as the input to the second stage hardware setup. Fig.18 shows the second stage hardware setup which is a high efficient MOSFET Bridge AC to DC converter. The output of the AC to DC converter is regulated by a DC-DC converter and then stored in an energy storage system. This stored energy is used to power LEDs which can be used for illumination.

Table II shows the performance comparison of various AC to DC converters in Experimental analysis used for harvesting energy from piezoelectric transducer. The proposed MOSFET Bridge AC to DC converter with switch control shows a maximum efficiency of 89.2%.

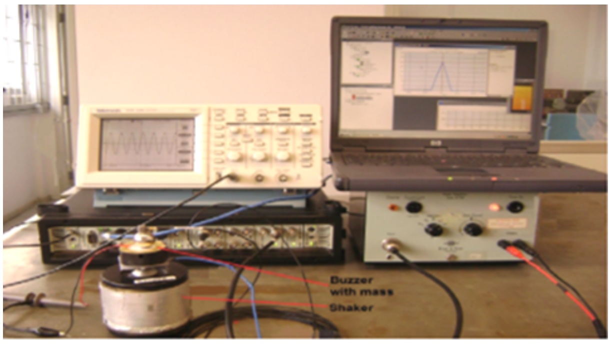


Fig. 17. Electromagnetic shaker and Piezo electric energy harvester

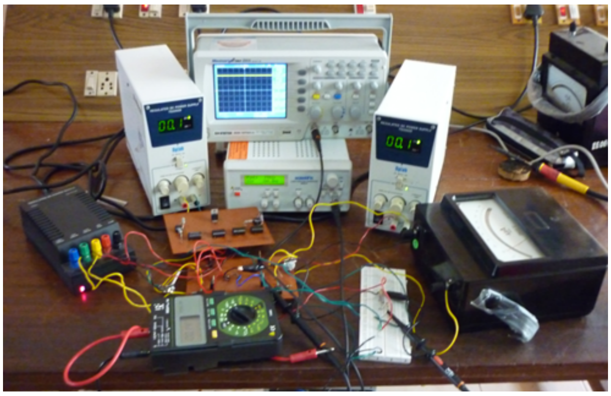


Fig. 18. Experimental setup of MOSFET Bridge AC to DC converter with switch control

Table 2. Experimental Analysis of AC to DC converters

Parameters	Diode Bridge	MOSFET bridge AC - DC Converter	MOSFET bridge AC to DC Converter With Switch
Input Voltage (V_P)	2.01V	2.16V	3.07V
Input Current (I_P)	200μA	200μA	200μA
Output Voltage	1.12V	1.26V	2.4V
Output Current	47μA	52μA	83μA
Input Power	146.12μW	157.03μW	223.18μW
Output Power	52.64μW	65.52μW	199.2μW
Efficiency	36.02%	41.7%	89.2%

8 CONCLUSIONS

This paper presents the performance evaluation of various rectification schemes for piezo-electric generator. The performance of various AC to DC converters such as Diode Bridge AC to DC converter, MOSFET Bridge AC to DC converter, and MOSFET Bridge AC to DC converter with switch control are analyzed using PSpice Schematics and the corresponding efficiencies are calculated. From the simulation results obtained, the MOSFET Bridge AC to DC converter with switch control has the capability of extracting more power from the transducer with superior efficiency. In addition by increasing the dimension of the crystal the power output from the transducer can be increased.

The proposed AC to DC converter can be used in applications such as self-powered system suitable for mobile applications like a wrist watch, mobile phones, Pico-radio and other hand-held devices. It can also be embedded in walkways to recover the energy of footsteps, embedded in shoes to recover walking energy to power sport sensors. In high-traffic areas like subway stations, shopping malls, theatres, stadiums and sidewalks, piezoelectric crystals with increased size can be embedded in staircases and floor tiles. These individual generators are linked together. As crowds of people walk through the area and generate force, this system collects the energy. In isolation, the small charges are immaterial, but together, they can power electronic appliances or be stored for future use. The stored energy can be used for powering LEDs used in illumination.

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