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PIEZOELECTRIC ENERGY HARVESTING RECTIFYING CIRCUITS COMPARISON

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ABSTRACT

The voltage that generated from piezoelectric cantilever is dependent on the magnitude of vibration source and the resonant frequency. In order for the AC electrical energy that derived from the oscillated kinetic energy source to be used for powering electronic devices, it needs to be rectified to DC. Full wave rectifying bridge using conventional diode is a popular choice for its simplicity and ready availability, however at low level output voltage that generated from piezoelectric energy harvester, it would not be able to perform the function because the voltage level that generated could be less than that required to operate the diode. Therefore low voltage operated rectifying circuit is crucial for piezoelectric energy harvesting application. This paper discusses on a few rectifying circuit to compare their performance and it shows that a MOSFET active switching circuit has the higher AC to DC power conversion efficiency compared to other conventional rectifying circuits.

Keywords: piezoelectric energy harvesting, AC to DC converter, low power micro-generator.

INTRODUCTION

There are abundant of ambient energy around us such as physical motion, heat flows, visible light, ocean waves and more which can be converted into useful electrical energy. One of the popular electrical energy generations is via mechanical to electrical energy conversion in the form of vibration as described by Beeby *et al.* [1].

The used of energy harvesting is intended to minimize the maintenance works in replacing limited life-span battery as usually it would be installed in wireless sensor nods which work in a big number and mounted in inaccessible locations. Vibration energy harvesting used transducers to harvest small-scale ambient energy. One of the popular methods is to use piezoelectric in the form of a cantilever operates at its resonant frequency to harvest maximum electrical output power. The output power that generated is in the range of hundreds micro-Watts to several milli-Watts. Generally, as smaller the scale of ambient energy harvester or micro-generator, the smaller the output power generation therefore is not suitable to be used for supplying continuous electrical power to bulky electronic system. There are many applications that suit to the description as mentioned, one of which is described by Bong Y.J and Kok S.L [2] demonstrate the application of piezoelectric energy harvester for powering ADXL335 accelerometer. Another application was studied by Chen L. *et al.* [3] where they used piezoelectric energy harvester to operate low power microcontroller CC2430 with RF transceiver function for wireless sensor networking application.

In real application, the acceleration level of ambient vibration is relatively low (in the range <1*g*), therefore it may not be compatible with conventional rectifying circuit using diodes with voltage drop of 0.7 V. Therefore, if the vibration source is too low, the voltage generation would be lower than the minimum requirement of the diode voltage drop and fail in capturing low level vibration energy. There are many literature discussing on rectifiers with higher input voltage generated by piezoelectric energy harvester [4, 5, 6], however, in this paper, the problem faces by micro-generator or energy harvester which generate low electrical voltage at low *g*-level orlow magnitude of vibration source is addressed. AC to DC power conversion efficiency is compared between a range of rectifying circuits consisting of conventional diode, zener diode, schottky diode, multiplier, MOSFET and active rectifier.

RECTIFYING CIRCUITS

The standard full bridge rectifier is a simple circuit commonly used for vibrational energy harvesting. It simply consists of four diodes forming a rectified signal across a capacitor smoothing the DC voltage. The total input AC power from the piezoelectric energy harvester is equal to the power deliver to a resistive load before rectification, P_L and the power that dissipate through the rectifier, P_D, which can be written as Equation(1) and Equation(2) respectively, while Equation(3) is the DC power after rectification.

$$P_L = V_L \cdot I_L \tag{1}$$

$$P_D = R_D \cdot I_L^2 \tag{2}$$

$$P_{DC} = V_{DC} \cdot I_{DC} \tag{3}$$

where V_L and I_L is the voltage and current deliver to a resistive load before rectification and R_D is the equivalent resistance of the rectifier, while V_{DC} and I_{DC} is the resultant of DC voltage and current after rectification. The rectification efficiency,η of a bridge rectifier is given by the ratio of the output DC power to the total input AC power supplied to the circuit from the piezoelectric energy harvester as given in Equation(4), which can be derived as in Equation(5) [7].

$$\eta = \frac{P_{DC}}{P_L + P_D} \tag{4}$$

$$\eta = \frac{V_{DC} \cdot I_{DC}}{V_L \cdot I_L + R_D \cdot I_L^2} = \frac{V_{DC}^2}{V_L^2} \cdot \frac{1}{1 + (R_D/R_L)} \tag{5}$$

where $I_{L(AC)}$ is rms value of load current before rectification and R_L is external resistive load.

The concept of voltage multiplier is similar to the standard full bridge rectifier which comprised of diodes but with additional capacitors that potentially producing high DC voltage from a lower AC source. The voltage multipliers are made up of multiple stages of RC circuit. Each stage comprises of one diode and one capacitor. In an ideal case, the total output voltage is equal to the voltage produces by a standard full bridge rectifier and multiplied bythe n-stage of the multiplier.

Voltage multiplier or charge pump can be categorized into three different topologies; Villard multiplier (half-wave series multiplier), Dickson multiplier (half-waver parallel multiplier) and full wave series multiplier. Villard multiplier is the most common circuit compared to others,this is because it is very versatile and has uniform stress per stage on diode and capacitors. In the other hand, parallel multiplier comes in small size yet highly efficient. At every successive stage, the voltage stress on capacitor is increased. The full wave series multiplier is highly efficient and has uniform stress. Same as Dickson, at every successive stage, the voltage stress on capacitors is increased.

The efficiency of a voltage multiplier is depended on a few factors. One of which is the finite value of the output resistance of the charge pump, P_{res}, the dynamic losses depend on the switching frequency and the overall parasitic capacitance of the charge pump, P_{dyn} and the short-circuit power consumption of the phase drivers, P_{sc}, which can be derived as [8],

$$\eta = \frac{P_{out}}{P_{out} + P_{res} + P_{dyn} + P_{sc}} \tag{6}$$

In most energy harvesting applications, the amount of energy harvested is relatively low to directly power the load, thus the system need highly efficient intermediate subsystem. In order to convert the power output from piezoelectric to a stable DC power, the efficient power conditioning circuit is required. Since the voltage drops across diode based rectifier is relatively big for energy harvester therefore low power and voltage drop rectifier is desirable.

Active rectification is one of an alternative to replace diodes with actively controlled switches; for this case power MOSFETs. The p-n junction diodes constantly drop the input voltage typically between 0.7V and 1.7V which is not just affect the AC-DC conversion efficiency but also impede low power micro-generator. MOSFET has very low resistance when conducting and since the voltage drop across the MOSFET is much lower, therefore the power loss can be reduced thus increase the efficiency [9].There are also other improvements on low power rectifier circuit such as synchronized switch harvesting inductor [10, 11, 12] which have been reported to have significantly lower forward voltage drops and the ability to raise low-voltage input to the levels needed for some low power electronic applications.

EXPERIMENTAL SET-UP

The experimental set-up for investigating the performance of the rectifying circuits is first determining the characteristic of the piezoelectric cantilever as the energy harvesting AC source. The piezoelectric cantilever beam obtained from Piezo Systems, Inc. with a dimension of 7cm x 3cm x 0.15cm and weight of 14g is being used in the experiment. The resonant frequency of the piezoelectric cantilever is determined by measuring the maximum output voltage generated from the device when tested under base excitation. The set-up is shown in Figure-1(a) and the schematic diagram is shown in Figure-1(b). The piezoelectric cantilever is mounted on the Labworks ET-126 electrodynamics shaker. The input from the shaker is connected to the function generator in order to drive the shaker at desired input frequency. As the output power from the function generator is low, therefore Labworks PA-138 linear power amplifier is used to amplify the signal so that it is enough power and drive the electrodynamics shaker to measurable level of excitation. The output voltage generated by the piezoelectric cantilever under shaker excitation is measured using a digital oscilloscope.

The measurements were conducted for a vibration excitation with frequencies ranging from 10Hz to 100Hz. By varying the resistive loads (R_{LOAD}) which is connected to the piezoelectric transducer, the V_{RMS} output voltages were recorded.

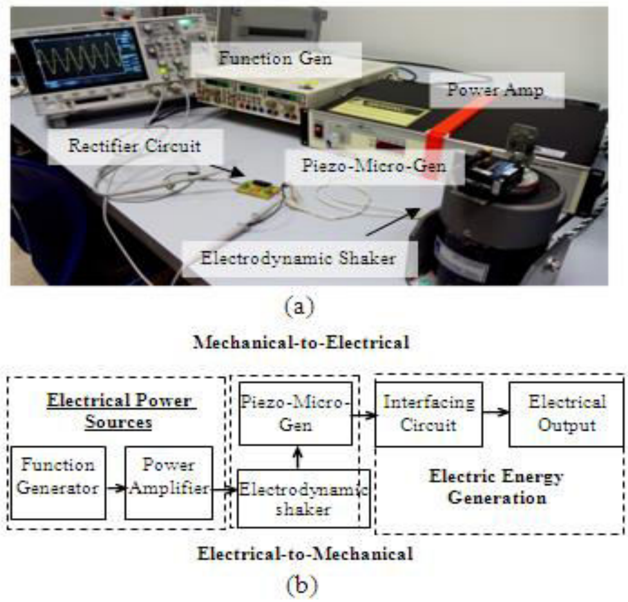

Figure-1. Experimental set-up for the piezoelectric cantilever beam energy harvester characterization, (a) photograph of the set-up and (b) the schematic diagram of the measurement.

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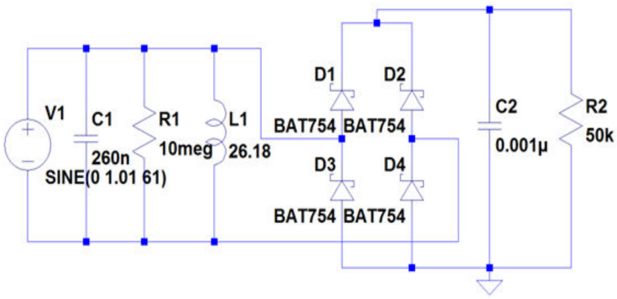
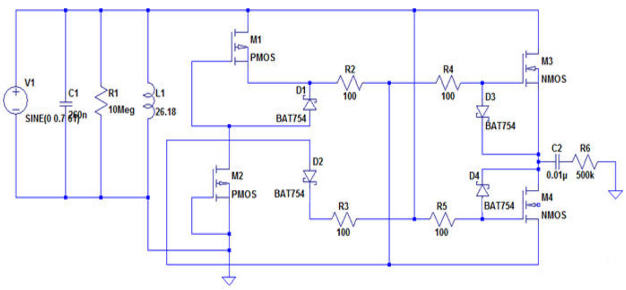
A series of experiments are conducted to determine the characteristics for the piezoelectric energy harvester. One of which is to vary the oscillation frequency, at a fixed *g*-level to determine optimum output voltage at open-circuit condition. Next the resistive load, R_{LOAD} is varied to determine the highest optimum output power and varying *g*-level at fixed frequency to determine the optimal resistive load R_{LOAD} relative to the oscillation amplitude.

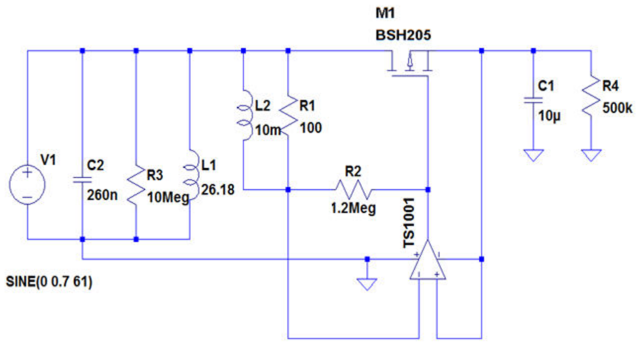
Once the characteristics of the piezoelectric cantilever is determined, a fixed value of oscillated excitation resemble to ambient vibration source will be fed into a rectifying circuit. For this paper, a series of rectifying circuits will be investigated for itsAC to DC conversion efficiency. First a series of passive bridge rectifiers as shown in Figure-2(a) and (b), constructed by using conventional diode (1N4001), Zener diode (1N750), Schottky diode (BAT754) and MOSFET will be examined and compared. Two level of vibration amplitudes; 0.1 g and 3 g will be used to investigate the performance of the rectifying circuits. This will follow by comparison of AC to DC conversion efficiency with active rectifier as shown in Figure-2(c). Finally a series of voltage multiplier is studied to determine the maximum optimum output voltage condition.



(a)



(b)



(c)

Figure-2. LTSpice Schematic diagram of (a) a Schottky full bridge rectifier, (b) MOSFET full bridge rectifier and (c) an active rectifier.

The circuit is setup to be operated at low voltage levels with operating frequency is at resonance frequency. It is assumed a weak coupling between the electrical and mechanical system which is implied that the resistive load has no effect on the mechanical displacement. The output power and the output voltage are compared between all these topologies. The simulation results and experimental results are also compared.

EXPERIMENTAL RESULTS

Firstly the piezoelectric cantilever is characterized as shown in Figure-3, whereby the resonant frequency of the cantilever structure is found to be around 60Hz and the maximum output voltage at 1MΩ is about 2.2V when excited to an acceleration magnitude of 3*g* (1*g* = 9.81ms^2). The output voltage of the piezoelectric energy harvester is proportional to the excitation magnitude. When the device is excited at 0.1*g* to its resonant, only 80mV of output voltage is measured.

Figure-4 shows a comparison of simulation results and experimental results for open circuit voltage after rectification using conventional diode full bridge circuit. It shows that the simulation results are in a good agreement with the experimental results. Full bridge rectifier constructed using schottky diode (BAT754) performs better than conventional diode (1N4001) and zener diode (1N750). MOSFET as constructed in passive circuit in Figure-2(b) performs the worst as it is operated at its optimum. However, when operated together with active components as in Figure-2(c), the efficiency increases drastically as shown in Figure-8.

The output power of the energy harvester can be measured across external resistive load. The optimum resistive load is found to be about 10kΩ however the magnitude of the output power is depended on the rectification circuit. Figure-6 shows that the schottky diode rectifier circuit able to produce about 5 mW compared to conventional diode which is reduced to half of its value.

In another series of experiment, voltage multiplier is being used to pump up the output voltage of the piezoelectric energy harvester. Half wave parallel

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voltage multiplier performs better than half wave series and full wave series type of voltage multiplier at a stage number of 8 with maximum output voltage of 3.5V as shown in Figure-7.

Figure-8 shows the summary of the experimental results. For passive rectifier circuit, schottky performs better compare to others, as the resistance of the schottky diode is less than the others therefore it has higher conversion efficiency, which is in agreement with Equation (5). Active rectifier using MOSFET switching operation performs the best among all the others rectifiers.

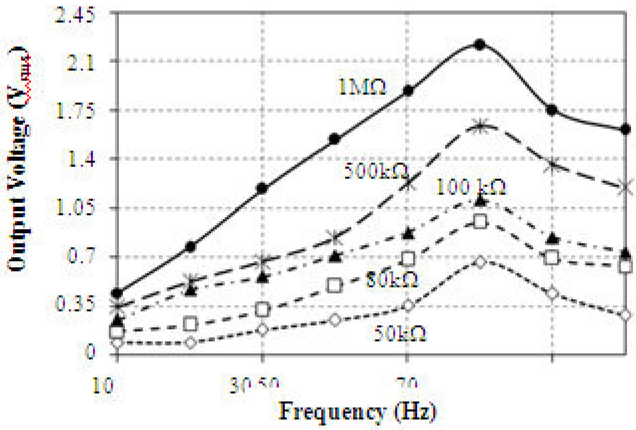

Figure-3. Frequency response of the piezoelectric energy harvester across different external resistive load at acceleration level of 3*g*.

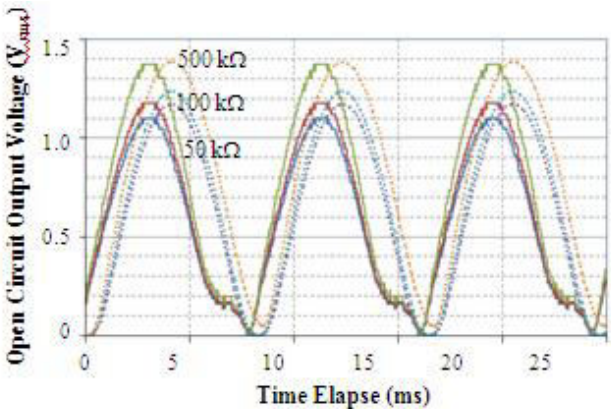

Figure-4. Simulation (dotted line) and experimental results comparison of an open circuit output voltage generated from the piezoelectric cantilever oscillated at 60 Hz.

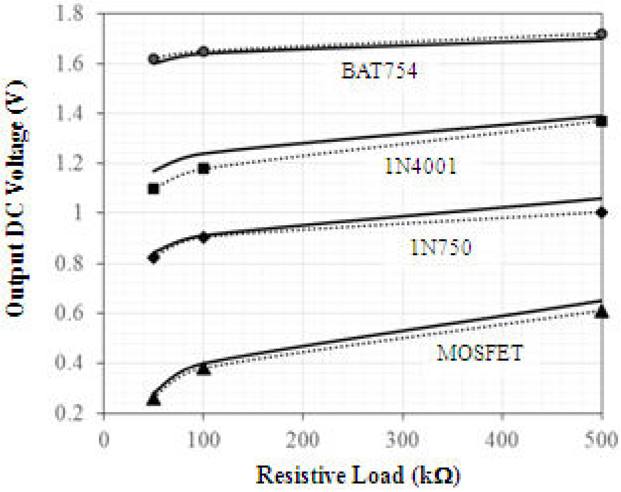

Figure-5. DC voltage output at various resistive load of a bridge circuit with different switching component excited at 3-g.

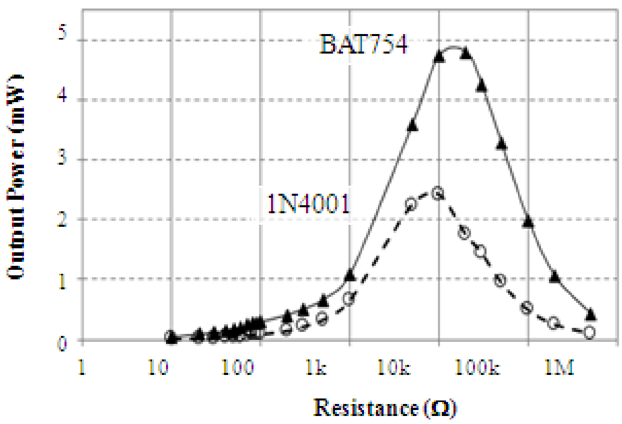

Figure-6. Output power comparison of diode 1N4001 and Schottky diode BAT754.

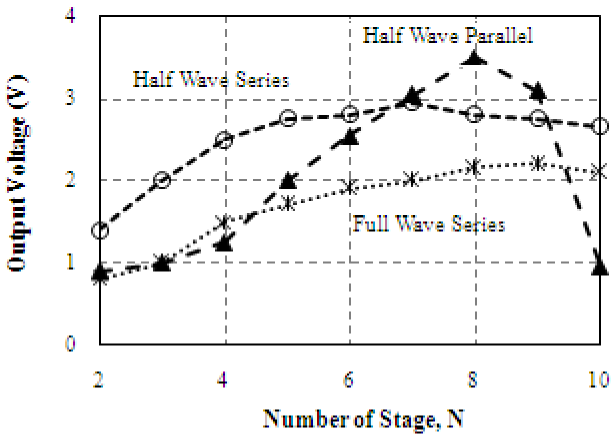

Figure-7. Output voltage as a function of the number of stage of a voltage multiplier.

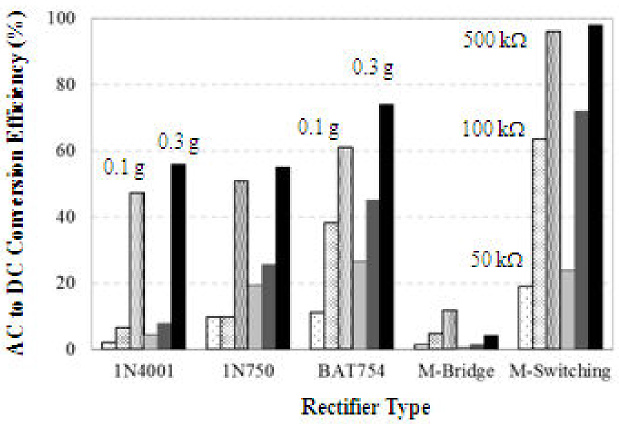

Figure-8. Comparison of rectifier types and their AC to DC conversion efficiency at various resistive load of 50 kΩ, 100 kΩ and 500 kΩ. Patterned bars represent excitation at 0.1 g while shaded bars represent excitation at 3 g.

CONCLUSIONS

From the experiment, it shows that active rectifier using MOSFET switching operation performs better, in terms of AC to DC conversion efficiency, than passive rectifier. It is also proof that schottky full bridge rectifier perform better than other diodes, due to the lower internal resistance of the element, which is in good agreement of the theoretical equation.

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