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Evaluation of Power Storage Circuit for Piezoelectric Energy Harvester in Impact Mode

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ABSTRACT

Power storage circuit is crucial to the performance of the vibration energy harvesting system as it will affect the amount of energy that can be harvested. The objective of this paper is to discuss the design and evaluation of power storage circuit for the vibration-based impact mode piezoelectric energy harvester. The proposed power storage circuit consists of rectifier circuit with rectifier capacitor, voltage regulator and the storage device. Evaluation on the rectifier circuit and the power storage circuit is carried out with variation in the resistive load and some other components. Results show that for the multiple impact input, full wave rectifier produces higher output than that of the other circuit. In addition to that, the proposed storage circuit can produce a stable output voltage and output power at about 40 Hz of operating frequency range. This show that piezoelectric energy harvester in impact mode can operate well with the proposed power storage circuit.

1. Introduction

Power storage circuit is crucial to the performance of the energy harvesting system. The storage circuit can be divided into two types; the active and passive circuits. The selection can be based on many subjective criteria. For the vibration energy harvesting using piezoelectric device, the main criteria should be the output energy that the harvester can produce [1-3]. The difference of both types of storage circuits is the existence and non-existence of the active device in the circuits. In general, passive circuit has no active device and this made it simple in design. While for the active circuit, the presents of the active devices such as electronic switches have made it more complex than the passive circuit.

In general, both storage circuits have their own advantages and disadvantages. For the passive storage circuit, its main advantages are simple in design, independent from the needs of external power sources and dissipate low energy. However, this circuit is lack in the efficiency. On the other hand, the active storage circuit is relatively more efficient than the passive one. Even though its

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efficiency is higher, in terms of design complexity and energy dissipation, the active storage circuit is far behind the passive circuit. Moreover, even in some of the cases, external power sources are needed to back up the operation of the active devices in the circuit.

The output power of the impact mode energy harvester is in the range of approximately below than 6mW. Comparison made by [4] shows that for the same volume of transducer, solar energy can produce 40 times higher electric power than the vibration energy would do. Thus, unlike solar energy, vibration based piezoelectric energy generation is more suitable with passive storage circuit as reported previously [5-9].

In general, storage circuit of piezoelectric energy harvester consists of rectifier circuit, voltage regulation circuit and lastly the storage device. The output of piezoelectric energy harvester is an AC signal. The rectifier circuit converts the AC output of the energy harvester into DC signal. In general, diode rectifier circuit can be divided into two types; the full wave rectifier and half wave rectifier circuit. It is known that the full wave rectifier circuit is more efficient in converting AC into DC signal. There are many literatures which discuss development of power storage circuit with the use of full wave diode rectifier circuit as the converter [10-14]. Apart from these circuits, voltage doubler circuit is also capable of converting the output to DC signal [16-19].

Voltage regulation circuit is an important part where input voltage produces by piezoelectric device will be regulated so that a stable voltage can be achieved and supplied to the load. This part can be as simple as having a linear regulator device [5] (for the passive circuit) or it can be very complex with control circuits and other functional circuits (for the active circuit) as reported in [14] and [21,22].

Based on the recent study it is seen that the focus is mainly for the design of power storage circuit of the piezoelectric energy harvester that operate in the continuous mode. Therefore, the focus of this paper will be on the evaluation of full wave rectifier and voltage doubler for the rectification of the voltage produced by the piezoelectric device operating in impact mode and the design of the storage circuit with the application of the ultra-low power buck power management IC for vibrations energy harvesting (MB39C811) developed by Fujitsu Semiconductor Limited. It is suitable to be used for light, piezoelectric and electro-mechanical energy harvesting.

2. Rectifier Circuit

The power storage circuit that we proposed is shown in Figure 1. It consists of rectifier circuit with rectifier capacitor C_{rect}, voltage regulator circuit and the storage device C_{stor}. The evaluation of rectifier circuits is presented in this section.

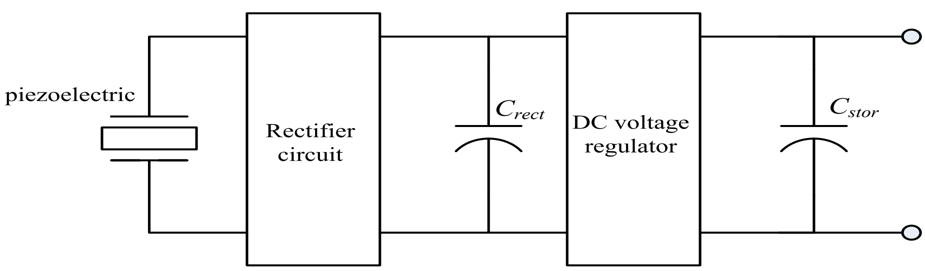
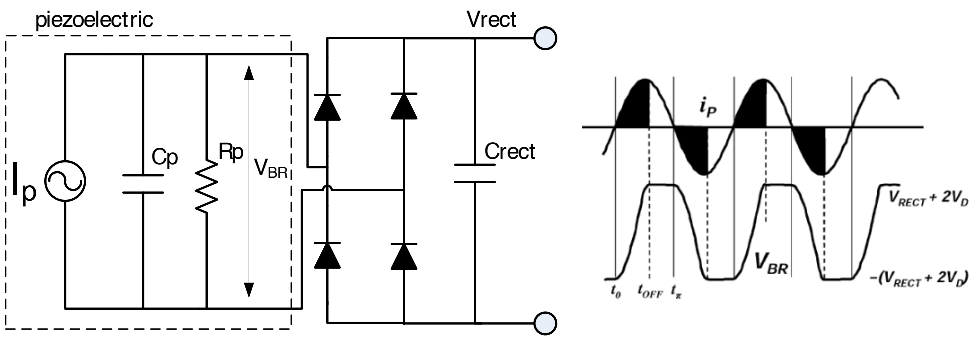


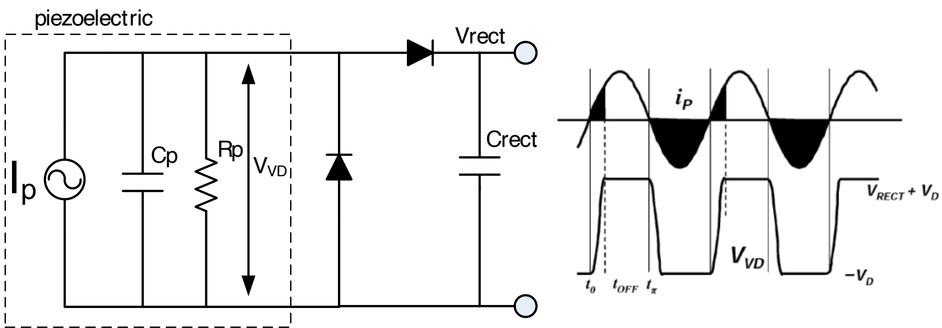
Fig. 1. Power storage circuit

2.1 Rectifier Circuit

This section will discuss the evaluation of the rectifier circuit for the energy harvester. As mentioned earlier, rectifier circuit can be modelled as full wave diode rectifier circuit or diode voltage doubler circuit. As illustrated in Figure 2, a full wave rectifier circuit consists of four diodes while voltage doubler circuit will have two. The equivalent circuit of piezoelectric energy harvester can be modelled as current source connected in parallel with the internal capacitance and resistance [17] or a voltage source connected in series with the internal capacitance [16]. Let us assume the equivalent circuit of the energy harvester and their associated simulated voltage and current waveforms is as illustrated in Figure 2. It is noted here that the shaded area under the plots represent the non-operation states of the rectifier circuits.



(a) Full wave diode rectifier



(b) Voltage doubler circuit

Fig. 2. Rectifier circuit configurations and their associated simulated voltage and current waveforms [17]

In the case of full wave rectifier circuit in Figure 2(a), the t=t_0 to t=t_{off} is the time where all the charges generated by the piezoelectric device flow into the internal capacitor C_p. During this period of time, the rectifier circuit is under non-operation condition (reverse biased) as no charge flows into C_{rect}. As the magnitude of voltage at C_p reaches V_{rect}+2V_D (V_D is the forward bias voltage of diode), the rectifier diodes begin to operate and as C_p discharge, the C_{rect} will be charging up. This occurred from t=t_{off} until t=t_π. As can be seen, during this period of time current i_p is in the decline mode. When the reverse cycle of the current i_p starts, the C_p starts to be charging up again until it reaches the magnitude of –(V_{rect}+2V_D). Once V_{BR}=–(V_{rect}+2V_D), another set of diode rectifier will operate and C_{rect} will be charging up again in the reverse direction.

The same process takes place in the voltage doubler circuit. However, in contrast with the full wave rectifier circuit operation, the time taken for the diode in the circuit to operate is shorter than in the full wave rectifier. The reason for this is because the maximum voltage of C_p is only $V_{rect}+V_D$. However, in terms of operation time of both circuits, it is obvious from the figures that the operation time of the full wave rectifier circuit is longer than that of the voltage doubler circuit. Experimental evaluation of both circuits will be presented in the next section so that effectiveness of both circuits can be evaluated for the impact mode piezoelectric energy harvester designed in this work.

2.2 Experimental Evaluation of Rectifier Circuit
2.2.1 Single pulse input

The purpose of this evaluation is to find out which rectifier circuit is best for the designed energy harvester. The factor of rectifier capacitor C_{rect} in the energy transfer also will be evaluated for each rectifier circuit. In it reported in [21] that for the optimum energy transfer of piezoelectric energy harvester, the rectifier capacitor C_{rect} needs to be approximately three times of the internal capacitance C_p. The energy equation is denoted by Eq. (1).

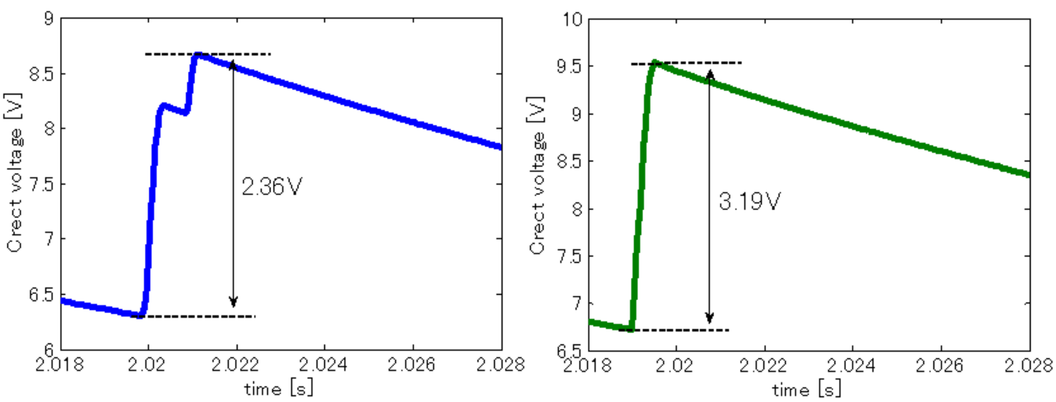
$$E_0 = \frac{1}{2} C_{rect} V_{rect}^2 = \frac{8 I_p^2}{\omega^2 C_p} \frac{(C_{rect}/C_p)^2}{(1+C_{rect}/C_p)^4} \quad (1)$$

From the equation, the maximum E_0 can be obtained if the ratio of C_{rect}/C_p is $3/1$. The evaluation performed by Yang *et al.,* [19] is based on the single pulse vibration input as denoted by Eq. (2).

$$I_p(t) = \begin{cases} I_p \sin \omega t \ , & 0 \le t \le T \\ 0 & , \quad t > T \end{cases} \quad (2)$$

To evaluate the energy transfer of single impact of the energy harvester by both rectifier circuits, below experimental conditions were used. Variation in the value of the rectifier capacitor C_{rect} was also carried out. It is noted here that from the actual measurement, the internal capacitance of the piezoelectric device is about 25 nF. Three times of this capacitance is 75 nF. Based on the availability of the device, we have chosen 0.1 µF capacitor as the ideal capacitance value for the evaluation.

Time response of one voltage pulse at C_{rect} is shown in Figure 3. This output response was measured when C_{rect} equal to 0.1 µF. Increment in the voltage by the full wave rectifier circuit is 2.36 V. And for the voltage doubler, the increment is 3.19 V.



(b) Full wave rectifier (a) Voltage doubler

Fig. 3. Voltage output of single pulse input of full wave and voltage doubler circuits

The energy accumulated at the rectifier capacitor from one impact can be calculated using Eq. (3), where in this equation *V* can be regarded as the voltage difference.

$$E = \frac{1}{2} C_{rect} V^2 \tag{3}$$

Using this equation, the energy accumulated by the full wave rectifier circuit is 278 nJ while the voltage doubler circuit produced energy of 508 nJ. It is obvious in this evaluation results that for one pulse energy transfer, voltage doubler circuit is capable of transferring higher energy than the full wave rectifier circuit. This is due to the difference in the number of diodes in the voltage doubler when compared to the number of diodes in the full wave rectifier circuit. Table 1 summarized the energy accumulated at the rectifier capacitor for different value of capacitance using full wave rectifier and voltage doubler circuit.

Table 1
Comparison of accumulated energy at rectifier capacitor from one impact

Rectifier capacitor		Full wave rectifier	Voltage doubler
1.	1nF	123nJ	137nJ
2.	0.1μF	278nJ	508nJ
3.	4.7μF	5.87nJ	8.46nJ
4.	47μF	2.35nJ	1.90nJ

Variation in the value of the rectifier capacitor resulted in different value of accumulated energy at the capacitor. As seen in the above Table 1, the optimum energy transfer was occurred when value of the capacitor is 0.1 μF. Another fact that can be interpreted here is that voltage doubler circuit is able to transfer more energy than the full wave rectifier at almost all the rectifier capacitor except at the value of 47 μF. The tendency for the capacitor with high value to accumulate higher energy for the full wave rectifier circuit can be seen in this result.

2.2.2 Multiple pulse input

In this section, the evaluation of energy transfer of multiple inputs by the full wave rectifier and voltage doubler will be presented. Even though the instantaneous energy transfer of single pulse input is more efficient using voltage doubler circuit, multiple pulses input seems to be different. If we look back to the simulated voltage and current waveform in Figure 2, the operating time of the full wave rectifier is slightly longer than that of the voltage doubler. Indirectly, it means that the non-operating time of the full wave rectifier is shorter and for the voltage doubler circuit, it is longer. Thus, longer in the non-operating time may results in efficiency reduction when load is connected to the circuits.

Evaluation of multiple pulses input of both circuits was carried out using circuit shown in Figure 4. Instead of rectifier capacitor, load resistor is connected at the output of the rectifier circuit so that the energy and power dissipation from the multiple pulses input by the load can be observed.

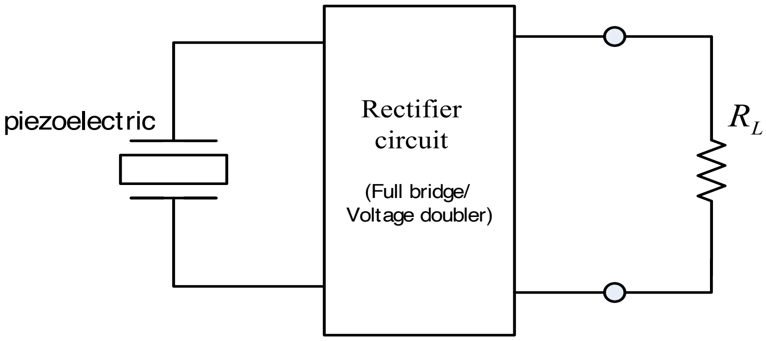


Fig. 4. Rectifier circuit evaluation – multiple impacts

Experimental conditions as listed in Table 2 were used. Instead of using fix load resistor, load that connected to the rectifier circuit was also varied. Thus, the effect of the load value, or in other words, the impedance matching of the circuit also can be observed.

Table 2
Experimental conditions

	Parameter	Value
1.	Base excitation frequency	40Hz
2.	Input base acceleration	1.36G
3.	Shim plate's radius	8mm
4.	Vibrating beam's spring constant	748.1N/m
5.	Proof mass's weight	11g

Figures 5 and 6 show the plots of output power and energy of the load of full wave rectifier and voltage doubler circuit. In the same figure, we also can see the output power and energy of energy harvester without rectifier circuit. From these figures, the capability of the full wave rectifier circuit to output higher power than the voltage doubler circuit by about 30% is shown. Another important point here is that, both rectifier circuits are dependent to a different value of matching impedance. The full wave rectifier circuit's matching impedance is approximately 14 kΩ while the voltage doubler circuit has matching impedance of 24 kΩ.

Besides that, the maximum power efficiency of the full wave rectifier and voltage doubler circuit drops approximately 18% and 48% respectively at their matching impedances. From the above experimental comparison, it was shown that even though the voltage doubler circuit can transfer higher energy from single input, in the multiple pulses input or to gain an optimum steady-state output, full wave rectifier is more efficient. Therefore, this work will consider of using full wave rectifier for the design of power storage circuit of the designed energy harvester.

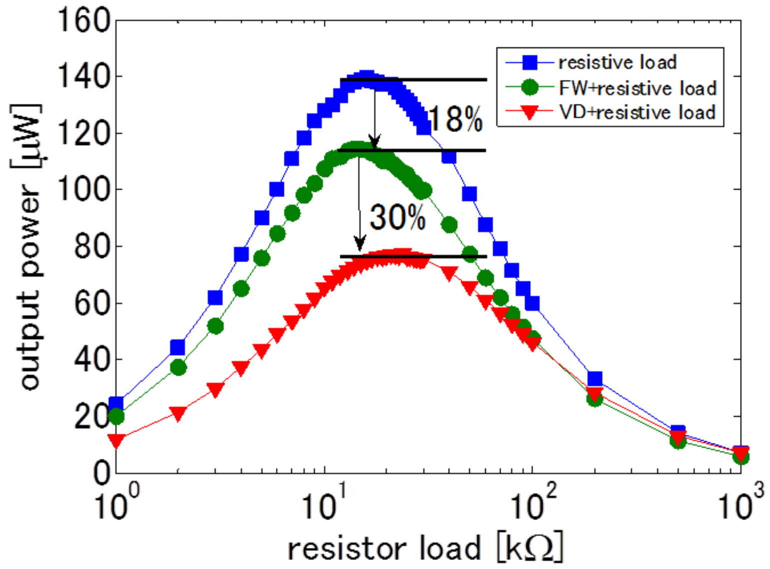


Fig. 5. Average output power for 0.5 s vs. load resistor

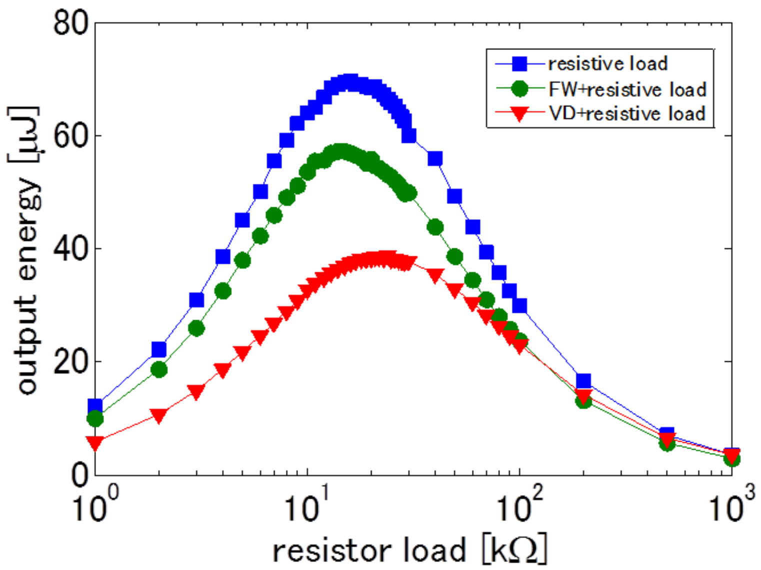


Fig. 6. Average output energy for 0.5 s vs. load resistor

3. Power Management Circuit

3.1 IC Block Diagram

The model of the voltage regulator circuit that used in this work is developed by Fujitsu Semiconductor Limited. It is the ultra-low power buck power management IC for solar and vibrations energy harvesting (MB39C811). This model of IC is suitable to be used for light energy harvesting, piezoelectric energy harvesting, electro-mechanical energy harvesting, wireless HVAC sensor and stand-alone nano-power buck regulator. It has integrated a full wave diode rectifier circuit in the IC. The minimum forward voltage of the diodes used in the IC is 150 mV. Thus, an external rectifier circuit is not necessary. Block diagram of the IC is shown in Figure 7. Besides the full wave diode rectifier circuit, the IC consists of a DC-DC Buck converter, a shunt circuit for protection from overloading and regulator circuit for power supply of the internal circuits. External switches can be used to set the desired value of output voltage. The selection of the output voltages is 1.5 V, 1.8 V, 2.5 V, 3.3 V, 3.6

V, 4.1 V, 4.5 V and 5.0 V. The range of the input voltage that the IC can receive is from the lowest of 2.6 V up to the highest of 23 V.

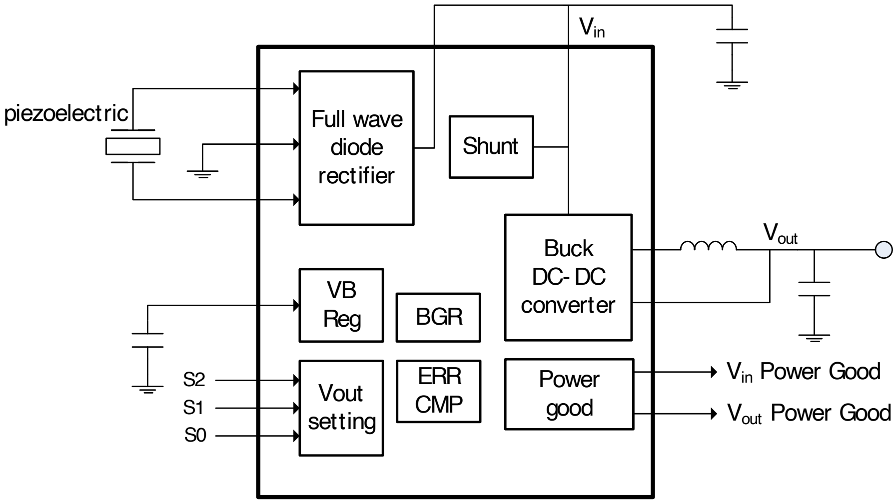


Fig. 7. Block diagram of MB39C811 power management IC

The typical connection of the power management circuit is shown in Figure 8. As shown in the figure, the AC voltage from the piezoelectric energy harvester is input to the AC2_1 and AC_2 pins. The input voltage is rectified by the rectifier circuit and its output is channel to the DCOUT2 pin. The other pin that connected to the DCOUT2 pin is the V_{in} pin. This connection allows the electric charges that accumulated in the capacitor to become energy source for the DC-DC Buck converter.

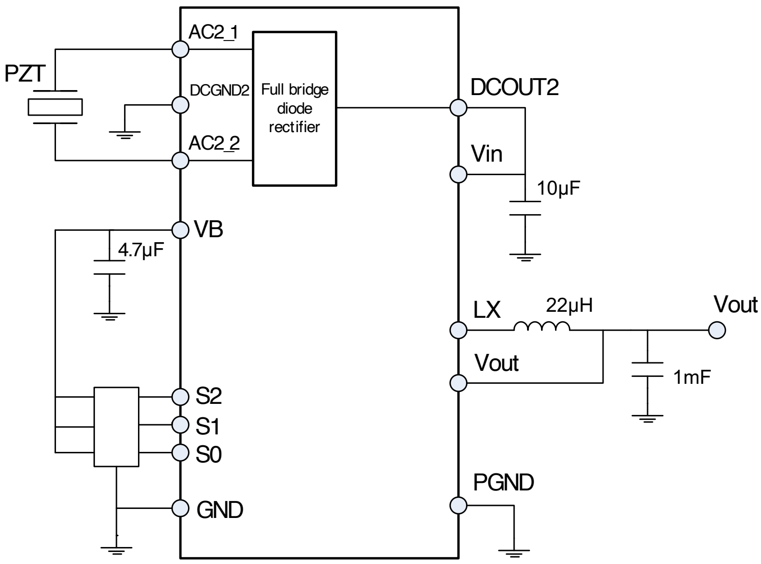


Fig. 8. Circuit connection to the IC

The operation of the IC is dependent on voltage at V_{in} pin. If the voltage level at this pin is 3.5 V or below than that, internal circuit will receive the power supply directly from the V_{in} pin. However, when the voltage level at the V_{in} pin is more than 3.5 V, the internal regulator is activated. Thus, internal circuit will get its power supply from this regulator. This operation will secure a stable output voltage even if there is voltage fluctuation occurred in the input voltage.

Capacitor which connected to the V_{out} pin served as the smoothing capacitor. At the same time, it is also act as the storage device. To ensure a relatively stable output voltage, a 1mF capacitor was used as the storage device. It is more convenient if a larger capacitor be used as the storage device so that more energy can be stored in it. However, this will lead to a longer charging time for the desired output voltage to be achieved.

3.2 Experimental Evaluation and Results

Figure 9 shows the open circuit voltage of the energy harvester against the base excitation frequency. The voltage starts to be output when the base excitation frequency is 40 Hz. The measurement of the open circuit voltage stops at frequency of 75 Hz due to the limitation of the power storage circuit that only can receive input voltage up to 23 V. It was recorded that the open circuit voltage of the piezoelectric energy harvester without the storage circuit is more than 23 V at the frequency of 80 Hz. It is obvious that the energy harvester can generate a stable output voltage of 5 V with the proposed storage circuit.

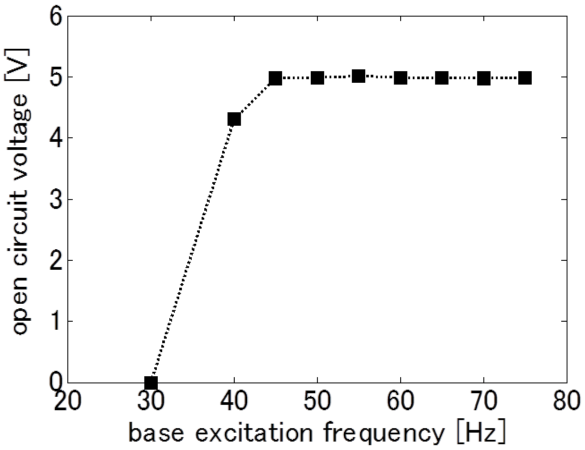


Fig. 9. Open circuit voltage of the energy harvester vs. excitation frequency

The V-I characteristic of the energy harvester with the application of the power management circuit is shown in Figure 10. The V-I characteristic was obtained with the base excitation input of 40 Hz. At this frequency, the base acceleration is equal to 1.36 G. As can be seen in this figure, the maximum voltage that can be achieved by this input is about 4 V and the maximum output current is approximately 8 µA.

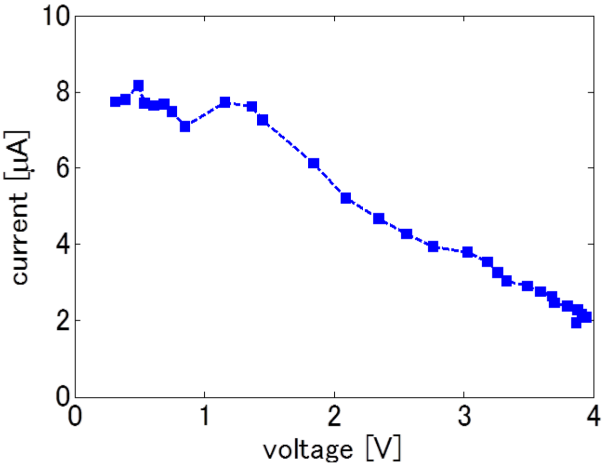


Fig. 10. V-I characteristic of the energy harvester

In terms of the output power, it is shown in Figure 11 that the maximum output power is achieved when the load impedance is about 200 kΩ. The maximum output power of about 11 µW is maintained at this level until the load impedance was increased to about 1 MΩ. Beyond this load impedance, the output power starts to decline. It was shown in this section that the proposed power storage circuit is able to regulate the output of the designed impact mode piezoelectric energy harvester to a stable and usable output.

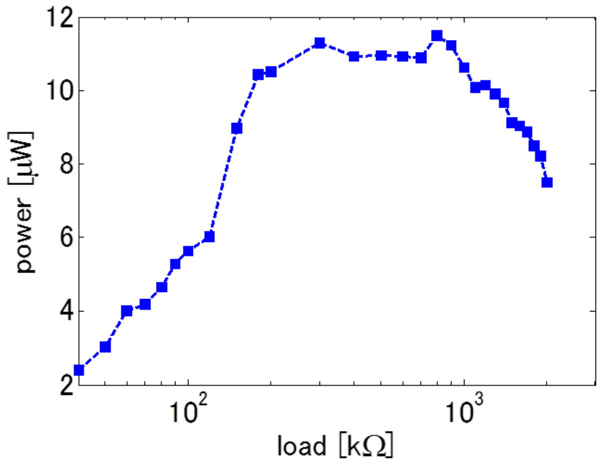


Fig. 11. Load vs. output power of the energy harvester

4. Conclusions

This paper has discussed the evaluation of the proposed power storage circuit for the designed impact mode piezoelectric energy harvester. The evaluation of the rectifier circuit shows that the full wave rectifier circuit is more efficient in rectifying the output of the energy harvester than the voltage doubler circuit. Overall, the implementation of power storage circuit shows a significant declination in terms of the output power of the energy harvester in impact mode. To overcome this issue, further evaluation on circuit for impact mode energy harvester need to be carried out so that the output of the designed energy harvester can further be collected.

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