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EXPERIMENTAL STUDIES ON THE PERFORMANCES OF AC/DC RECTIFIER CIRCUIT ON IMPACT-BASED PIEZOELECTRIC ENERGY HARVERSTER

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ABSTRACT

Recently, concerns on the energy consumption for ultra-low power energy has been rapidly increased. Piezoelectric energy harvester suffers from extremely huge power loss when rectifying the generated AC signal into DC voltage. This paper demonstrates a study on enhancing the efficiency of the interfaced rectifier circuit on Lead Zirconate Titanate (PZT) piezoelectric element that is actuated by using just a single impact force from a free-fall experiment. The purposes of this study is to reduce the power losses from this harvester system during rectification in order to increase the efficiency of the extracted output power from piezoelectric. The enhancements have been made based on the factors that affecting the generated output power from the piezoelectric. In this study, the interfacing converters comes from four different types of rectifier circuits that is optimized by varying the level of forward voltage,V_f drop across the diode and the capacity of the filter capacitor,C_f to match the impedances of the harvester. The enhancement of the generated output voltage from the harvester also has been done by altering the mechanical configuration of the set-up to increase the vertical displacement from the impact. The performances of the system have been analysed and plotted into voltage and power curves. From the experimental results, it shows that the power efficiency of the full-wave bridge rectifier with the lowest power losses across the diode is the highest compared to the other rectifier topologies.

Keywords: piezoelectric, impact-based actuator, energy harvester,power conditioning circuit,voltage doubler rectifier circuit, bridge rectifier circuit.

INTRODUCTION

Global demand for electricity have been increase rapidly as the world turns out to depend a lot on the technology, gadget and networking. All of this requires a lot of electrical energy which is currently being massively produce by harvesting the natural resources of geothermal [1], turbines [2], photovoltaic [3], and windmills [4]. The consequences from using this type of energy is that, they are leaving a gigantic footprint on the Mother Nature. This has alarmed and moved numerous researchers on these areas to find the best alternative solutions to replace the energy used to provide electricity.

Lately, the trends of recycling or scientifically known as harvesting waste energy; heat, vibration produced from human motion or machines have becoming prevailing. As we are already know, solar power offering the highest power density, but kinetic energy comes to second place after with a power density of 50 to 330 $\mu W/cm^3$[5]. Despite the energy produce is small, it able to power up the electronic device with a low power requirement quite all right [6]–[8]. Conventionally, these devices which are micromechanical system (MEMS) and Wireless Sensor Network (WSN) are limited by the batteries lifespan and hardly to access for maintenance.

Instead of powering them using a limited power source; battery, we can effectively use the wastes energy from human activities by converting the vibration energy into electricity using one of this three; piezoelectric, electromagnetic and electrostatic transducers [9]–[11]. From the studies, piezoelectric transducers are very highly recommended as it offering the highest output voltage much more flexible compared to the others.

There are some important factors that will affect the effectiveness of the harvester system. First, as we are already know the composition of the crystalline structure of the piezoelectric; mainly consists of Lead Zirconate Titanate (PZT),will generate electricity when there is deformation occurs on its surfaces. Another type of piezoelectric composite is Polyvinylidene Fluoride (PVDF). Between these two, the most suitable piezoelectric materials for impact-based application method are determined in term of their efficiency in producing electrical energy. PVDF has an advantage in term of flexibility when comparing to PZT, which is much more brittle than PVDF. However, PZT able to produce electricity much more efficient than PVDF in general. PZT structure can be deformed either by using a continuous vibration (d31-mode) where normally the transducer is in cantilever form or either by using impact force (d33-mode) on top of the material which will generate a pulse signal [12], [13].Studies shows that, natural characteristic of the vibration frequency (d31-mode) on the environment is in the range of 100Hz. However, cantilever beam piezoelectric transducer hardly to achieve their resonance frequency below the natural frequency exists in nature. In order to generate an optimum output power from the piezoelectric, the excitation frequency of the driving surface needs to operate almost near or match with the resonance frequency of the material. Meanwhile, for the impact-based (d33-mode) excitation, the variables that affecting the piezoelectricity is mostly depend on the mass and velocity applied and it can be applied to the low-frequencies application such as human body which normally generating within 10 to 30 Hz [14]. Therefore, in this study, the concept of harvesting raw energy especially from kinetic energy using an impact force instead of continuous vibration on piezoelectric device is chosen as it has become the most promising scheme for powering low-powered device within the ranges of microwatts (μW) to milliwatts (mW) [15], [16].

Most of the electronic devices in the market nowadays is powered by regulated DC voltage. As the generated output from the piezoelectric transducer is in AC form, therefore, rectification is required for it to be useful to power the devices [17]. The rectification system is conventionally consisting of few passive electronic components that affect the extraction efficiency of the electricity generated from the piezo to the load. This is also one of the important factor to be taken care of in enhancing the performance of the harvester in order to deliver an optimum power transfer between the transducer and the load.

In this paper, a method of enhancing the generated output power of piezoelectric electric energy harvester is demonstrated. The experiments are conducted by actuating the ceramic disk piezoelectric transducer using a weight-drop analysis. A force is applied on top of the piezoelectric using the relationship of three parameters which are height, mass and gravitational acceleration. As the paper more focusing on enhancing the power management unit, these three parameters will remain as a constant. To enhance the generated output energy from the impact-based piezoelectric energy harvester, the disk's setting base is designed with a hole on it. As a result, the generated output power become higher as the strain displacement of the disk also increased [18]. Efficient power consumption is a common issue in various fields, and the maximum power of a device is always an evaluation index. Therefore, this studies will focus on boosting the generated output power based on the choice of the rectifier circuit type, rectifier passive elements and the filtration unit. Lastly, the efficiency of the power performance by using different AC-DC converter topologies is analysed and compared.

IMPACT FORCE OF FALLING OBJECT IN WEIGHT-DROP ANALYSIS

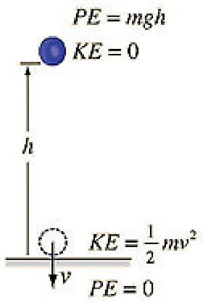
The underlying physics of the free-fall perseverance have been well understood for hundreds of years. Two equations, (1) and (2) are sufficient to classically represent the gravitational interactions between masses. The relationship between the mass of two point (M and m), their displacement (d) and the magnitude of the gravitational force (F) between them has been first discovered by Sir Isaac Newton described in Equation (1):

$$F = \frac{GmM}{d^2} \quad (1)$$

Newton's second law,

$$F = ma = m\left(\frac{dv}{dt}\right) = \frac{d(mv)}{dt} = \frac{dp}{dt} \quad (2)$$

which describes the acceleration, a, of a mass m, and velocity, v arising from the application of a vector force, F. The second law, although only valid in a classical regime of low velocity, it is sufficiently accurate to describe the action of the free-fall experiment.



$$K_E = \frac{1}{2}mv^2 \quad (3)$$

$$P_E = mgh \quad (4)$$

$$mgh = \frac{1}{2}mv^2 \quad (5)$$

Figure-1. Illustation of the conservation of energy of free-falling object.

All moving objects have kinetic energy (K_E); the energy possessed by the object due to the movement or motion when a force is applied. Simply put, if an object is at rest, it does not possess this type of energy. It can be measure by referring to the Equation (3), where the kinetic energy of an object is dependent on the two variables; mass, m and the velocity of the object, v. A small change in velocity able to affect a huge change on the kinetic energy as both of the variables are directly proportional to it. Equation (4) is the potential energy of the mass where it dependable on the height h. The higher the height of the mass, the greater the potential energy of it. From Figure-1, it can be seen that P_E and K_E can exists only once at a time. Therefore, it can be simplified as in Equation (5). When the height, h is known, the velocity can be found by simplified the equation into $v = \sqrt{2gh}$.

When two objects hit one and another, a number of possible outcomes can happen depending on the characteristic of the colliding objects; the mass, m and the bottom surface which is piezoelectric. There are three situations that normally will happen depending on the rigidity of the landing surface assuming that the dropping object is firmly structured. The penetrations on the ground surface impacted affecting the resulted output force of the piezoelectric based on the Equation (6). The resulted impact force is dependent on the impact depth, h_2 of the ground when it is in damping condition. It shows that the resulted force F is directly proportional to the mass of the object and velocity factors. Harder ground makes it less penetrates, thus higher impact force is produced. If it bounces back, the impact force is even higher because of the greater change in momentum.

$$F = \frac{K_E}{h_2} = \frac{mv^2}{2h_2} \quad (6)$$

Based on this mathematical expression, it can be say that the generated output power of the piezoelectric transducer is depends on the impact velocity of the object as well as the impact force of an object when the object's

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kinetic energy and momentum are constant. Regarding to these statement, in order to enhance the generated output power transfer from piezoelectric to the load using weight-drop analysis, the disk's setting based for piezoelectric is specifically designed to elevate the generated output energy from the piezoelectric. The purpose of leaving a hole underneath the transducer is to enhance the optimum power by increasing the displacement of the piezoelectric without being detained by the base[18].

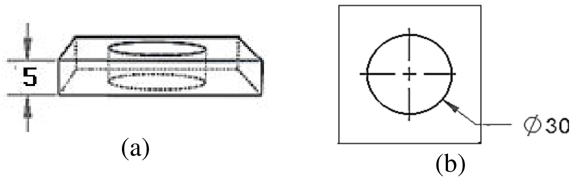

Figure-2. Cross-sectional diagram for piezoelectric transducer setting base (a) side view, (b) top view.

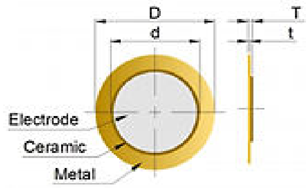

Figure-3. Dimensional drawing of Murata 7BB-35-3.

Table-1. PZT parameters.

Part Number : 7BB-35-3	
Capacitance (nF)	30.0
Plate, D (mm)	35.0
Ceramic, a (mm)	25.0
Electrode, d (mm)	23.0
Thickness, T (mm)	0.53
Plate thickness, t (mm)	0.30

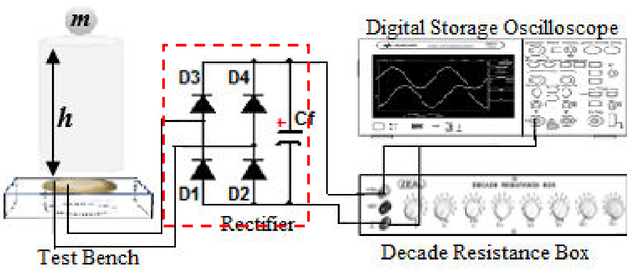

Figure-4. Overall experimental setup block diagram.

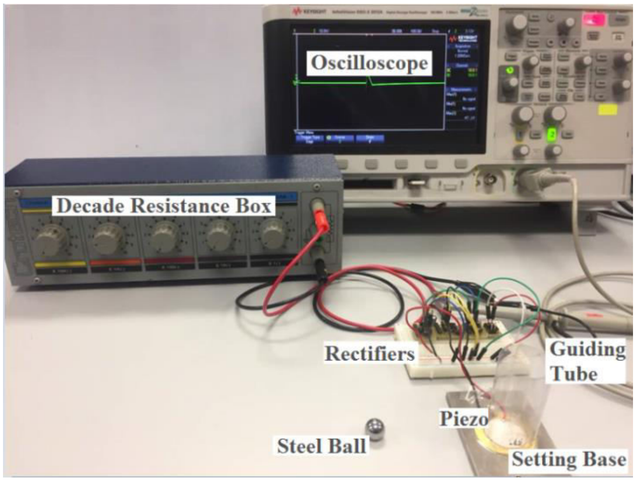

Figure-5. Experimental arrangement for piezoelectric energy harvester.

As the generated signal from piezoelectric is in sinusoidal form, it is normally restricted in producing the negative half cycle as the bottom surface is detained by the flat setting base. When there is a hole beneath the transducer, the transducer can generate higher negative half cycle as now the piezoelectric can bending downward more than before. Figure-2 shows the cross-sectional view of the proposed disk's setting base with a dimension of (50 x 50 x 5) $mm^3$and a hole of 30 *mm* in diameter. This configuration is one of the method to enhance the generated output power from the ceramic disk piezoelectric energy harvester.

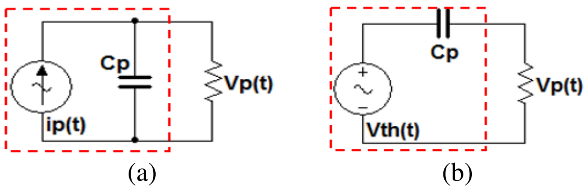

Figure-6. Piezoelectric equivalent schematic diagram (a) Norton, (b) Thevenin[19],[20].

PIEZOELECTRIC DISK SPECIFICATION AND ITS EXPERIMENTAL SETUP

Piezoelectric specification

The type of piezoelectric material, which is a PZT (7BB-35-3), (d33), from Murata Manufacturing Co. Ltd., is used in this experimental analysis with a specification of 30 *nF* internal capacitance as tabulated in Table-1. From the dimensional drawing of this transducer, it shows the composition of its important elements; electrode, crystallize ceramic and brass metal as shown in Figure-3. This type of PZT has high flexibility, performance and reliability as a harvester and sensor.

Experimental setup

The experimental setup for characterizing and evaluating the power potential of the transducer is illustrated with a schematic diagram and shown in Figure-

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5. The setup consists of a test bench (piezoelectric), energy conversion circuit (rectification and filtration unit) and the measurements equipment, KEYSIGHT, Digital Storage Oscilloscope (DSO-X 2912A) that is used to measure the generated output signal. The ceramic disk piezoelectric was gummed to an aluminium base with a hole of 30 *mm* beneath it which is then placed on a flat workstation. To actuate the piezoelectric transducer using impact, a rigid steel mass is dropped from a certain height. A guiding tube is used to increase the accuracy and repeatability of the resulted output. A wide range decade resistance box, from Cratech UK is used as a load to measure the generated output power.

As the free-fall test is conducted manually by human not by a machine, therefore the experiments for each parameter is conducted for several times and the average of each parameters is taken as the results. This is to ensure that the data taken are the most accurate and reliable. In this studies, the most important unit for power conditioning circuit; the rectification and filtration unit, is analysed into three different categories. This is the most crucial factor that will affect the extraction of the harvested output energy. Shown in Figures 4 and 5, the transducer is connected to the energy harvesting circuit; consists of rectifier diodes and a capacitive filter before connected to a decade resistive box which acts a load. Several series of experiments are conducted with the intention of enhancing the generated output power. Three types of diode, Zener (1N4728), Silicon (1N4007) and Schottky (1N5819) are tested as the harvester rectifiers for the first series of experiments. They will be constructed in full-wave bridge rectifier first as highlighted in the red box. The diode with the best performance will be selected to study the behaviour of different rectifier topologies by changing the configuration in the highlighted red box with Half-wave rectifier Full-wave bridge rectifier, Greinacher Voltage Doubler and Delon Voltage Doubler. In general, the parameters that have been analysed in this studies are the types of diodes selected for the rectifier unit, the rectifier topologies and its working principle and also the filtration unit. Details on this will be discussing more in the rectifier section later.

PIEZOELECTRIC EQUIVALENT CIRCUIT AND AC/DC RECTIFICATION SYSTEM

Piezoelectric equivalent circuit

The internal characteristic of piezoelectric transducer can be modelled as the internal capacitance, c_P of the transducer is connected in series with the voltage source or connected in parallel with the current source based on Thevenin and Norton theory respectively. Figure-6(a) and (b) shows the transducer's equivalent circuit diagram (within a red box) connected to a resistive load.

Most of the electronic devices in the market nowadays are powered by using DC power sources in the range of 3.3 to 5V. As shown in the schematics, the generated signals is in time-varying form, $Vp(t)$ which means that is not suitable for powering up a DC power source devices. Therefore, this AC signals need to be rectify first beforehand. A number of rectifier topologies of single-phase uncontrolled rectifying circuits and voltage doubling rectifying circuits have been investigated to enhance the output power of piezoelectric energy harvesting devices [21]. These include the characteristic of the diodes and optimum resistive load.

AC/DC rectification and filtration system

The ideal rectifier system signifies the goal of a real rectifier system, where it is basically a two-port network between an AC power source; which is a sinusoidal voltage sources according the generated output from piezoelectric, and a load. An ideal rectifier is theoretically to be lossless; therefore, all of the generated output power from the piezo at the input port is converted to dc power at the dc output port. However, in real-life situation, it is normally impossible and kind of very hard to get the same result as expected. This is due to the losses occurred in between of the system while transferring the energy.

In order to put everything in perspective, several varieties of known passive rectifier circuits including the performance and the limitations of the circuit are studied in this paper. Passive rectifier circuit can offer the advantages of simplicity, and durability which are the reasons of why choosing these circuits over any wide range rectification system. Several practical rectifier topologies chosen have been categorized as conventional rectifier and specialized voltage doubler are studied and analysed to determine their level of performance.

The conventional diode; half-wave and full-wave bridge rectifier are presented in Figure-7(a) and (b) respectively. There are named based on their working operation, where half-wave rectifier is only operating at one cycle which normally a positive half-cycle and full-wave bridge rectifier, is a composition of a bridge that allow the signal pass through for both cycle resulting a full-wave output signal. Whereas, the specialized rectifier that are designed to double up the input voltage are illustrated in Figure-7 (c) and (d), which are Greinacher Voltage Doubler and Delon Voltage Doubler; also known as half-wave and full-wave voltage doubler respectively.

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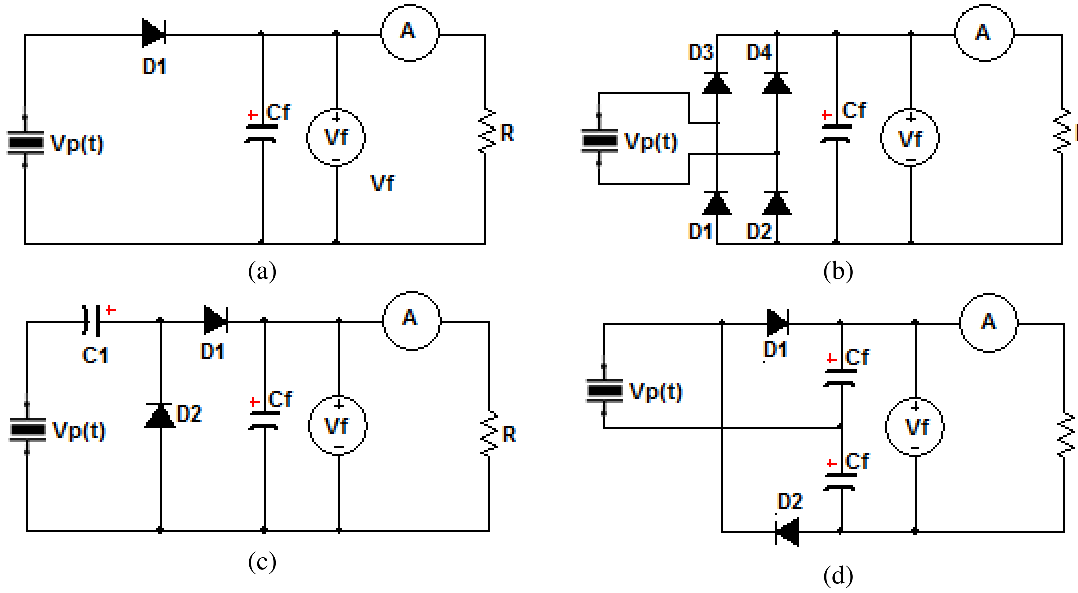

Figure-7. AC-DC converter (a) Half-wave rectifier (b) Full-wave bridge rectifier, (c) Greinacher Voltage Doubler and (d) Delon Voltage Doubler.

Normally, all of the circuits mentioned are used to rectify a continuous sinusoidal signal. However, in this study, the experiments are set up for only one single impulse signal from the drop test analysis.

The harvester equivalent circuit in Figure-6 is represent as an ideal ac voltage sources, $V_p(t) = V_{in}\sin(\omega t - \theta)$. Right after rectification, the resulted output is normally becoming positive cosine form, where the negative cycle from the sinusoidal signal is inverted or clipped by the diode to make it become positive. This can be represented in term of Fourier series in Equation 7 and 8 for half-wave and full-wave rectifier respectively.

$$f(t) = \frac{A}{\pi} + \frac{A}{2} sin\omega_0 t - \frac{2A}{\pi}\sum_{n=1}^{\infty}\frac{\cos(2n\omega_0 t)}{4n^2-1} (7)$$

$$f(t) = \frac{2A}{\pi} - \frac{4A}{\pi}\sum_{n=1}^{\infty}\frac{\cos(n\omega_0 t)}{4n^2-1} (8)$$

where, A is the magnitude of the input signal.

For specialized rectifiers case, the generated output signal is the same as the full-wave bridge rectifier, but the only different is the multiplication becomes twice the value of the source. Both of the circuits in Figure-7 (c) and (d) producing an output of twice the peak value of the *Vp(t)*. Thus, $V_{out} = 2V_m$, where V_m is the maximum rectified voltage. Although both of the application is double up the input voltage, there are big different is the circuit construction. For the Greinacher Voltage Doubler, diode D1 and D2 conducting at different cycle. During the positive half-cycle of the input signal, diode D1 is forward biased, charging the capacitor C1 up to the peak rectified voltage, V_m. While during the negative half-cycle, diode D2 is forward biased and conducts charging capacitor C2. At this moment, capacitor C1 is in series with the input voltage that results in adding the stored voltage with the input voltage to the capacitor C2 that equal to $2V_m$. Meanwhile, the construction of full-wave Delon voltage doubler is actually consists of two conventional half-wave rectifier with opposite polarity but the working operation is almost the same as Greinacher. The Fourier Series of both of this circuit can be express as in Equation (9).

$$f(t) = \frac{A}{\pi} + \frac{2A}{2}\sum_{n=1}^{\infty}\sin\frac{n\omega_0 t}{2} n\omega t (9)$$

As mentioned previously, the factors that affecting the harvested output power are the characteristic of the diodes chosen, the rectifier topology and the resistive load. Therefore, the studies are divided into two part, part A; analysing the performance of the diode characteristic and part B; analysing the rectifier performances based on different configuration.

RESULTS VERIFICATION AND DISCUSSIONS

Based on the configurations set up in Figure 4 and 5, two sets of experiments are conducted and has been categorized in part A and part B. As have been discussed before, the generated output voltage from piezoelectric transducer is in AC form. To validate this statement, a test has been conducted by dropping a steel ball with 1-gram mass on top of the piezo from 50 *mm* height, by connecting the piezo in open-circuit connection directly to the oscilloscope. This can be seen from Figure-8 that illustrates the generated waveform in AC form where it has the negative part and the positive part. Thus, this validate the statement that piezoelectric transducer producing an output voltage in AC form. The generated signal has been captured and recorded in a single run control operation with the sampling time of 100ms. The oscilloscope was set to trigger only when the generated output is greater than 10V to avoid mistaken noise or any external force as the signal. To distinct and focus only on enhancing the generated output with the same supply input, the parameters of the experiments; height of the drop, h, and mass of the steel ball, m, are kept constant throughout the analysis.

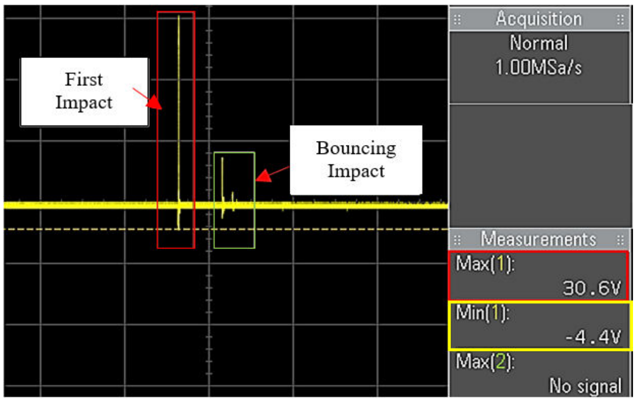

Figure-8. Generated AC output voltage of piezoelectric without the disk's setting base.

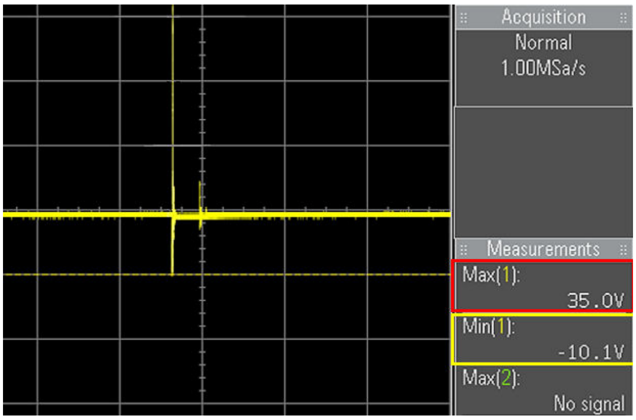

Figure-9. Generated AC output voltage of piezoelectric with the disk's setting base.

Mechanical configuration

In the free-fall event using a spherical mass, it is very likely to see the mass that is drop vertically will keep bouncing until the momentum of the ball decays to zero. The same analogy has been occurred in this experiment. The steel ball that have been impacted directly on the piezo, generating the highest instantaneous output voltage for the first impact and immediately the impact force is decreases until the ball stop bouncing. Back to the phenomenon of the nature, the kinetic energy when the ball was impacted on the piezoelectric is the highest according to the $\frac{1}{2}mv^2$. However, the momentum of the ball has been faded after the first impact as the potential energy, P_E of the ball is not as the highest as before dropping it. This can be easily interpreted by referring to Figure 8. The highest generated output voltage from a free-fall test with the $P_E = 490\mu J$ is 30.6Vmax. The generated output resulted from the momentum of the ball is neglected in this experiments as it is very small.

In order to enhance the generated output voltage, the piezoelectric was placed on two different arrangements; with and without disk's setting based mentioned in the previous section. The generated output voltage captured when the transducer is placed directly on top of the test bench is shown in Figure-8 while the one that has been sets on the disk's setting base is in Figure 9. From these figures, the outcomes have been highlighted in the yellow and red box under the Measurements sections with the reading of the instantaneous maximum and minimum output voltage, Vmax and Vmin. The reading from Figure 8; without the setting base is actually lower than the reading of piezoelectric gummed on the disk' setting base with a 30 *mm* hole beneath it in Figure-9 with the potential difference of almost 5V. Not just that, the negative cycle of the first initial impact also becomes higher from -4.4Vmin to -10.1Vmin. Therefore, this proves that by increasing the displacement of the piezoelectric, the generated output voltage also will be increase accordingly. This is due to the characteristic of the piezoelectric based on the relationship between the electric displacement, D_3 resulted from the strain S_3 based on equation $D_3 = d_{33}S_3$, where d_{33} is the piezoelectric strain constants which normally resulted from the vertical impact displacement and S_3 is strain along the x-axis. When d_{33} is constant, the strain S_3 will affect the changes on the electrical displacement and D_3 is directly proportional to the strain S_3. Therefore, for the rest of the experiments, the transducer is tested by using the disk's setting base to enhance the harvested output energy.

Rectifier

A rectifier converts an AC signal; that composed of positive and negative cycle in one period of time, T which normally in the form of sinewave and sometimes, in square or triangle wave depends on the application into a DC signal, that provides a constant voltage in only one polarity; either just negative or just positive. Normally, the electronic devices sell in the market working on DC power source. However, the generated output voltage from piezoelectric is in AC form. Therefore, this signal needs to be converted first into DC. Figure 10 shows the resulted output waveform of the rectified piezoelectric signals without being connected to any load. The transducer's AC signal is rectified using a conventional full-wave bridge rectifier and as can be seen from the figure, the resulted output waveform is only at the positive part of the oscilloscope. Although an ideal DC voltage should be illustrated in a straight horizontal line, but need to mention here that the input supplied to the rectifier from piezoelectric is just at an instance. Therefore, the rectification result also only exists at the moment the ball hit the piezoelectric.

Part A: Diode characterization performance on full wave bridge rectifier

In this series of experiments, a full-wave bridge rectifier is tested by constructing it using three different type of diodes. This is to analyse the performances of the proposed diode; 1N5819, 1N4007 and 1N4728. Table-2 shows the specifications of the diodes used in this test. The rectifier circuit is connected in between the piezoelectric transducer and a decade resistance box with a range of

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10Ω to 100kΩ as a variable load without a filter capacitor, C_f. The purpose of using this full-wave rectifier configuration is mainly because of the fact that this rectifier utilized both cycle from the input sources. In the first half of the AC cycle, D3 and D4 conducts together to pass the signal through as they are forward biased. Meanwhile, in the second half cycle; negative half, D1 and D2 are forward biased this time. Due to the net effect of the bridge rectifier, the negative part of the input signal is inverted to become positive.

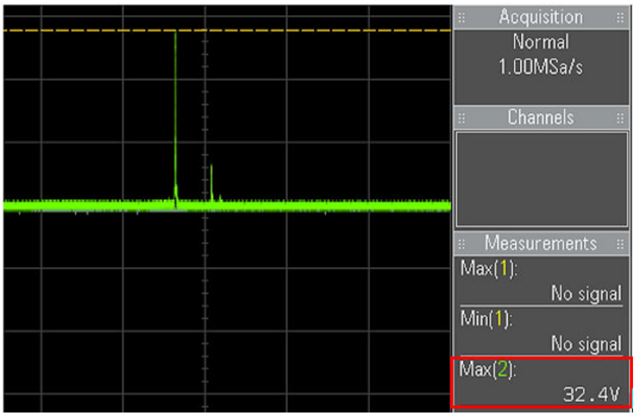

Figure-10. Generated rectified output voltage of the full-wave bridge rectifier.

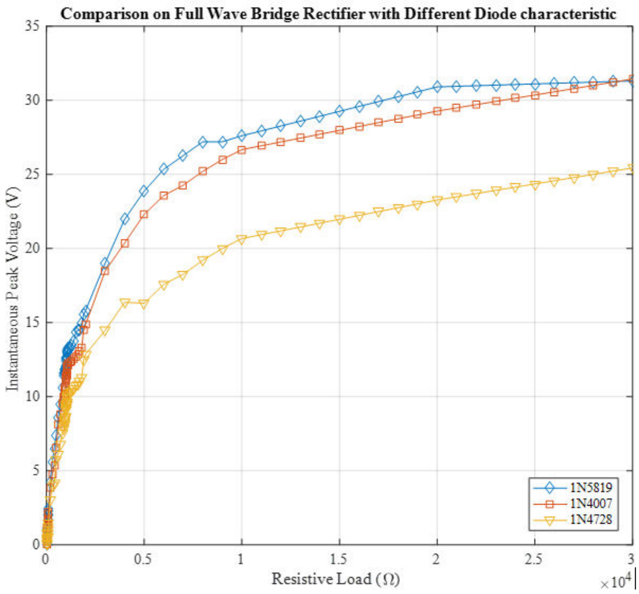

Figure-11. Instantaneous output voltage of full-wave bridge rectifier with different type of diodes.

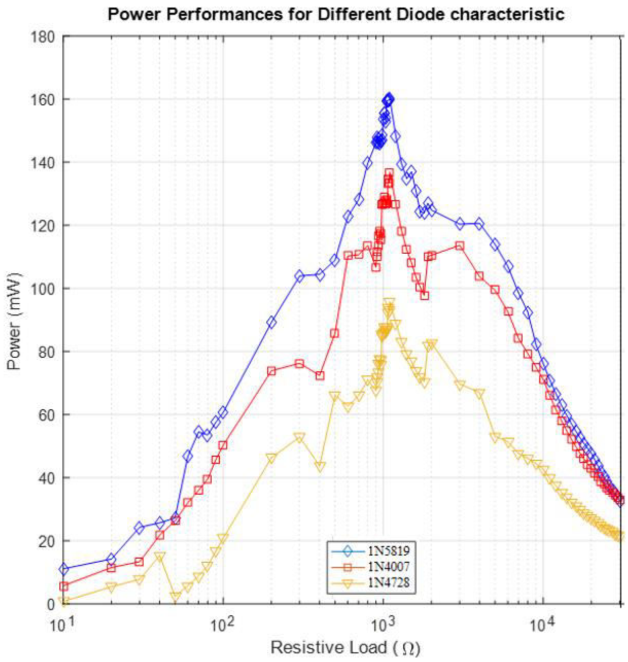

Figure-12. Generated output power of the rectifier against the resistive load

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Table-2. Diodes Specification.

Parameter	**Description**		
Manufacturer Product number	**Vishay 1N5819**	**Vishay 1N4007**	**M.C.C 1N4728**
Diode Type	Schottky	Silicon	Zener
Forward voltage $V_f(V)$	0.6	1.1	1.2
Forward current $I_f(A)$	1.0	1.0	0.2
Peak reverse voltage (V)	40	1000	75
Peak reverse current (mA)	0.001	0.000005	0.0001
Diameter (mm)	2.7	2.7	2.80
Length (mm)	5.2	5.2	4.5

The output voltage from the full-wave bridge rectifier is around 32.4Vmax as shown in Figure-10 when using 1N5819 Schottky diode. However, when the rectifier circuit is excluded from the harvester (piezoelectric connected directly to the oscilloscope) the resulted output voltage is 35.0Vmax. There was some voltage drop on the diode during the rectification process. Based on the voltage equation around a single loop of a voltage source, V_S, voltage across the diode, V_D and voltage across the load, V_L, we can see that the output voltage, $V_O = V_L = V_S - V_D$.That is the reason why the generated output voltage not the same as the supplied input voltage.

To test the efficiency of the system, the rectifier circuit is connected to a decade resistance box to varies the load and the resulted output voltage is measured accordingly. The voltage curves of how the selected diode performed in a single impact drop test analysis on piezoelectric is plotted against the resistive load as in Figure-11. As can be seen from the graph, the full-wave bridge rectifier that is constructed with Zener diodes has the lowest generated output voltage of at least 19.09% compared to the maximum output voltage of rectifier using Schottky and Silicon diode. For the other two diodes, performances of rectifier constructed by the Schottky diode are slightly higher than the one constructed using Silicon diode with 0.42% difference. It turns out that there is not a big difference between these two. From the plotting curves also, we can see that, the legends of Schottky and Silicon diodes starts to saturates at the magnitude of 31Vmax.This is due to the generated output voltage from the piezoelectric in open-circuit connection is around 35Vmax. From here, it can be concluded that, the voltage drop of the rectifier across the Schottky diode is smaller than the rest. As for each cycle, at least two diode is activated, therefore, when the value of forward voltage drop, V_f for each diode is added together, the output voltage equation will become, $V_L = V_O = V_s - 2V_D$.

As the value of the rectified output voltage and the value of the resistance at the load can be measured, we can calculate the output power of the circuit based on the power equation law, $P_L = V_L \cdot I_L$, where, $V_L$is the voltage and I_L is the currents across the load.The resulted output power of this rectifier circuit for each diodes specification can be depicted in form of power curves graph as in Figure-12. Since the load is a resistance, the voltage on the load is proportional to the current. By simply used the equation of Ohm's Law, $V = IR$, we can get the value of the current I_L, where $I_L = \frac{V_L}{R_L}$. Those circuits have the most optimum harvested output power when the resistive load is at 1.1kΩ, as shown at the peak of the curves. From the graph, Schottky diode still generating the highest optimum output power of 160mW, leading the Silicon and the Zener with17.18% and43.55% respectively.

The rectification efficiency, (η), is given by the ratio of the output DC power, P_{DC} to the total input AC power, $P_{AC} = P_L + P_D$, where P_D is the losses across the diode during rectification, which can be expresses by Equation 10 and 11.

$$\eta = \frac{P_{DC}}{P_L + P_D} \quad (10)$$

$$\eta = \frac{V_{DC} \cdot I_{DC}}{V_L \cdot I_L + R_D \cdot I_L^2} = \frac{V_{DC}^2}{V_L^2} \cdot \frac{1}{1 + \left(\frac{R_D}{R_L}\right)} \quad (11)$$

Therefore, the efficiencies of the harvested power of the full-wave bridge rectifier for each diode are 67.2%, 58% and 34.86%. From these results, it can be concluded as, the performances and efficiency of the circuit is affected mostly by the losses occurs during the process. Therefore, it is important to clarify and finds the most efficient component to be selected as the part of the circuit. In this case, Schottky has proved it credibility in term of performances, lowest voltage drops, V_f and efficiency. The outcomes from this test have been simplified in form of a table in Table-3.

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Table-3. Results of the diodes performances.

Parameter	1N5819	1N4007	1N4278
Max. peak output voltage(V)	33.73	32.23	25.97
Opt. peak output voltage (V)	13.27	12.33	10.07
Optimum resistor load($k\Omega$)	1.1	1.1	1.1
Opt. output power (mW)	160	136.79	95.82
Efficiency(η)	67.2%	58%	34.86%

Part B: Rectifier topologies performance analyzation

Later, the free-fall experiments are carried on by constructing the proposed rectifiers circuits using 1N5819, Schottky diodes in order to enhance the efficiencies of each topology. The configurations parameters still remain constants as the previous test. All of the proposed circuits are composed of 1N5819 diodes, an external variable load resistance box, and an electrolytic capacitor that acts as the ripple filter, C_f. For the specialized rectifiers; Greinacher and Delon voltage doubler, they are having an extra electrolytic capacitor to store the voltage at each half cycle. These capacitors affect the performances of regulating the output voltage, as it removes the ripple from the rectified output voltage.

The paper has mentioned that there are four types of rectifier topologies proposed in this experiment. After conducting the analysis on these circuits, it is found that, Greinacher circuits or half-wave voltage doubler circuit configurations are not suitable for a single impact input signal application like this drop test analysis. This is due to the working operations of this circuit itself. It needs to mentioned that, these circuit have been tested numerous time by directly connecting an AC power sources from a step-down transformer with 7.7V_{AC}. It able to double up the input voltage and rectified it into 15.3V as the results. The proves is shown in Figure-13. The yellow AC line is the input signals from the transformer with 50Hz frequencies in channel 1 with 5.00V/divisions. The rectified and doubled output voltage is captured by the green straight line in channel 2 with 10.0V/divisions. The waveforms are captured in 50ms time scales.

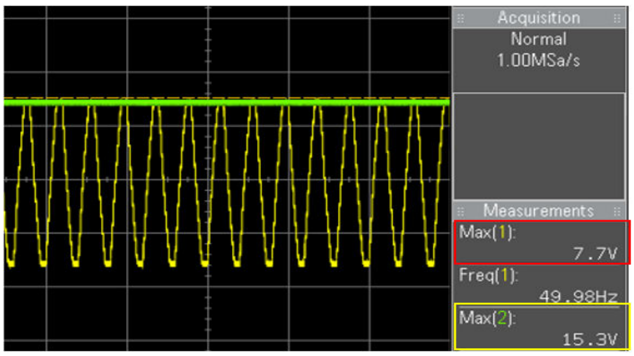

Figure-13. The input and output signals for half-wave voltage doubler.

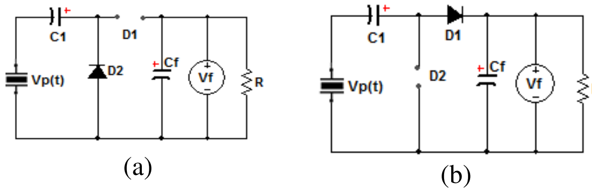

Figure-14. Greinacher working operations.

The working operations of this circuit have been analysed. From the observations, the cause is explained in term of comparisons on the continuous and single pulse inputs signal. This is basically because of the arrangement of the storage capacitor $C1$ and $C2$ as shown in Figure-7(c). Diodes D1 and D2 will be conducting simultaneously in each half-cycle of the input signal. They will never be conducting together. When these rectifier circuit is connected directly to a continuous AC sources, these diodes, will have the same conducting time to store the energy into $C1$and $C2$. Another main factor is because of these alternating AC signal from the transformer have an equal positive maximum value with the negative part. Therefore, when capacitor $C1$ releasing the stored voltage at the second half-cycle, the generated output voltage at capacitor $C2$ will become twice the input signal. However, this cannot be implemented when the sources are from piezoelectric that have been impacted by a single impact in drop test analysis. When the steel ball is impacted on the piezoelectric, for the first half-cycle, diode $D2$ is forward biased, while $D1$ is reverse biased, make it acts as an open circuit as shown in Figure-14. For the next half-cycle, which is for the negative part, diode $D1$ are now forward biased. As the negative part from the impact force of the piezo is literally smaller than the input signal, when it is added to the voltage stored in $C1$, the output capacitor will not be able to become twice the input signal. Besides, the stored voltage in $C1$ are now already discharge although not completely. Therefore, the results from this test will not be included in comparing the performances of the rectifier topologies and as can be seen from the plotted voltage and power curves in Figures-15 and 16, the legend is only regarding on the half-wave, full-wave bridge and Delon or also known as full wave voltage doubler rectifiers.

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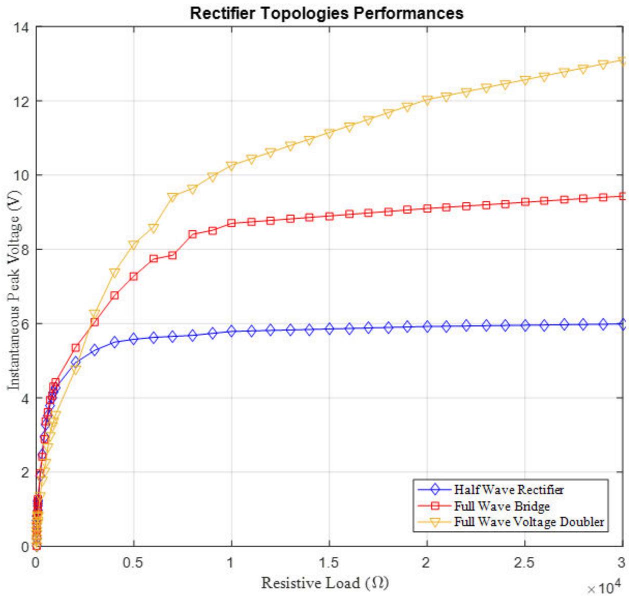

Figure-15. Instantaneous output voltage of the rectifier topologies.

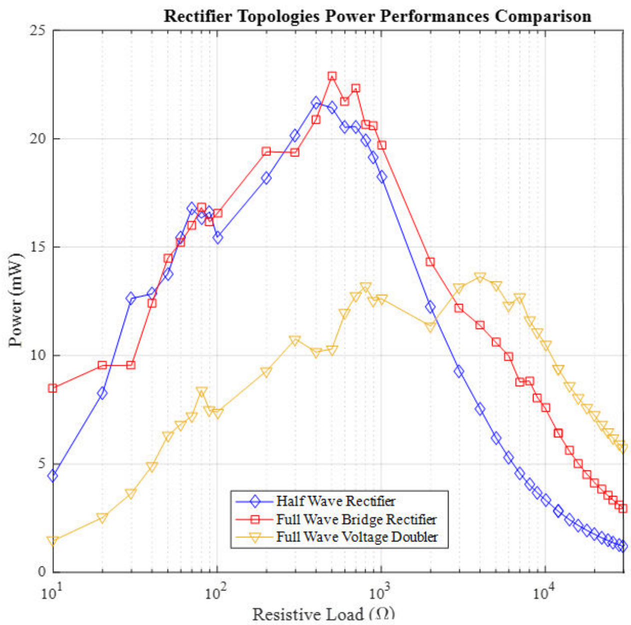

Figure-16. The performances of the power of different rectifier topologies.

Results of the measured rectified output voltage from the proposed circuits are plotted in Figure-15. It is observed that the generated output voltage of the rectifier is keep increasing and begins to saturate when the load higher than 10kΩ. This is due to the $V = IR$, where voltage,V is directly proportional to the load, R. Therefore, when the resistive load becomes higher, the generated output voltage also should be increases as well. In comparisons on the resulted output voltage for each rectifier topologies, there is at least 4V different between each of them. However, an ideal voltage doubler should be able to produce twice the amount of the conventional full-wave bridged rectifier. This is again back to the working operation of the voltage doubler and the harvested energy from the piezoelectric itself. The negative half-cycle from one impact force is too small to be able to generate the resulted output twice the input. But comparing to the resulted output voltage of the rest of the rectifier, voltage doubler still able to produce higher output voltage than them. The generated output voltage of half-wave rectifier is the lowest. This is because, half-wave rectifier clipped out the negative half-cycle of the input voltage from the piezo. When the rectified voltage is filtered by filtration capacitor, C_f, the capacitor C_f will be charged and immediately discharged as the input signal is only a pulse.

Figure-16 shows the power performances of the rectifiers against the resistive impedances to find the optimum resistive impedance of this circuit. It is found that the optimum resistive load for each rectifier is now differ from each other. The optimum resistive load for half-wave, and full-wave bridge rectifier are around 500Ω. For full-wave voltage doubler, it seems like it has two peak when it at optimum but the highest optimum peak is 1.1kΩ. From these plotted graph, it can be seen that the output power for full-wave voltage doubler, 13.335mW is the lowest compared to when we comparing them in term of output voltage which is 4.52V. This is due to the relationship of power, $P = IV$, where power is directly proportional to the current, I. As we are already know, ideally, the total power into the system is the same as the total power at the output of the system, $P_{IN} = P_{OUT}$. However, regarding to Ohm's Law, voltage is directly proportional to the load and the current. So, when the voltage of the voltage doubler is increases twice the amount of the input supplied, the current has also been cut down at least twice the amount in order to maintain the power equation. This is the reason why the resulted output power for the voltage doubler is the lowest here. Hence, in term of performances, voltage doubler has the least efficiency compared to the other topologies. Table-4 summarized the founding of this experiments of half-wave (HWR), full-wave bridge (FWBR) and full-wave voltage doubler (FWVD).

Besides that, the value of the filter capacitor,C_f also affects the performances of the harvester management circuits. The higher the capacitance value of the C_f, the lesser the voltage ripple of the rectified signal according to the equation $V_{ripple} = \frac{I_L}{f \cdot C_f}$. However, for a single impact application as in this experiment, the larger the capacitance value ofC_f, the longer the time it will take to store the energy into the capacitor. Therefore, it is inconvenient to choose a very big capacity of C_f as the stored energy is only an instantaneous output voltage from the piezoelectric.

Table-4. Results of the different rectifier topologies.

Parameter	HWR	FWBR	FWVD
Max. peak output voltage(V)	5.82	9.1	13.10
Opt. peak output voltage (V)	3.27	3.38	4.52
Optimum resistor load$(k\Omega)$	0.5	0.5	1.1
Opt. output power (mW)	21	23	13.335

CONCLUSIONS

Series of experimental evaluation with respect to the efficiency of rectifying circuit on impact-based piezoelectric energy harvester system was conducted and discussed in this paper. The aims of this studies to enhance the optimum output power of the system. A piezoelectric transducer that has been impacted vertically with a velocity of $3.13156 m/s$ able to generate an instantaneous peak voltage of 35V from 50 mm high in open circuit configuration. In order to make the generated energy usable to power up the dc regulated electronic device, some rectifier topologies have been tested. From a branch of AC-DC converter available, half-wave, full-wave bridge, Greinacher, and Delon rectifier have been selected in this test. The experimental results from this study has been discussed critically. Firstly, as the rectifier is mainly the composition of number of diodes, the voltage rectifier circuit were optimized by varying the values of the forward voltage of the diodes. Three different diodes are selected, and it is found that Schottky diode has the highest performance compared to Silicon, and Zener. Secondly, a test on the comparison of the efficiency and generated output voltage and power of the selected rectifiers have been done. For both half-wave rectifier and Greinacher voltage doubler, they are not suitable to be used for impact-based excitation technique due to their working operations. In particular, the full-wave bridge rectifier circuit shows the highest power efficiency of $23mW$ compared to Delon voltage doubler circuit with $13.335mW$; although it able to generate twice the voltage of full-wave bridge rectifier.

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