An Improved Rectifier Circuit for Piezoelectric Energy Harvesting from Human Motion

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Featured Application: Energy harvesting applications, low-voltage rectification, active rectification for charging small storage devices from human motion.

Abstract: Harvesting energy from human motion for powering small scale electronic devices is attracting research interest in recent years. A piezoelectric device (PD) is capable of harvesting energy from mechanical motions, in the form of alternating current (AC) voltage. The AC voltage generated is of low frequency and is often unstable due to the nature of human motion, which renders it unsuitable for charging storage device. Thus, an electronic circuit such as a full bridge rectifier (FBR) is required for direct current (DC) conversion. However, due to forward voltage loss across the diodes, the rectified voltage and output power are low and unstable. In addition, the suitability of existing rectifier circuits in converting AC voltage generated by PD as a result of low frequency human motion induced non-sinusoidal vibration is unknown. In this paper, an improved H-Bridge rectifier circuit is proposed to increase and to stabilise the output voltage. To study the effectiveness of the proposed circuit for human motion application, a series of experimental tests were conducted. Firstly, the performance of the H-Bridge rectifier circuit was studied using a PD attached to a cantilever beam subject to low frequency excitations using a mechanical shaker. Real-life testing was then conducted with the source of excitation changed to a human performing continuous cycling and walking motions at a different speed. Results show that the H-Bridge circuit prominently increases the rectified voltage and output power, while stabilises the voltage when compared to the conventional FBR circuit. This study shows that the proposed circuit is potentially suitable for PEH from human motion.

Keywords: piezoelectric energy harvesting; human motion; H-Bridge rectifier; rectification; self-powered device; MOSFETs

1. Introduction

Energy is a basic need in modern human life. Its demand is rapidly increasing in recent years to support various human activities. It is universally acknowledged that there is a limitation on the use of fossil fuels. Thus, many scientists and researchers are consistently searching for new energy sources. A wide range of options are available in the environment, namely, thermal [1], solar [2,3], wind [4], and mechanical energy [5,6]. Recent emergence of handheld and wearable electronics boosts the demand for ubiquitous, low energy sources [7]. Generating electrical energy (EE) from mechanical energy (ME), such as structural vibrations is an active area of interest, which is made practical by the progressive reduction in power consumption of portable electronic devices. Vibrational energy is readily obtainable from a wide range of sources such as bridge carrying traffic, machinery in operation, aircrafts or automobiles in motion, wind induced vibration, and human motion. The use of these renewable energy sources could potentially reduce or even
eradicate the need of chemical batteries, thus exerting a positive impact on human life and environment.

Piezoelectric materials received wide attention in this application because of their unique piezoelectric effect, which is capable of converting ME, in the form of vibration, into EE, in the form of alternating current (AC) voltage. A typical piezoelectric energy harvesting (PEH) system involves an electromechanical system [8] (such as a piezoelectric device (PD) attached to a cantilever beam), a source of mechanical vibration, electronic circuitry and a storage device/load. A flow chart illustrating a typical PEH system is demonstrated in Figure 1.

![Figure 1](image_url)

**Figure 1.** A flow chart of illustrating a typical piezoelectric energy harvesting (PEH) system.

When the PD is subjected to mechanical excitation, it generates AC. To power any electronic device, such as mobile phones, LED bulbs, charging batteries, or wristwatches, a stable direct current (DC) voltage is necessary. For this reason, the AC voltage generated by the PD needs to be converted into DC voltage with the use of an AC-DC rectifier circuit. In the literature, several adroit circuits have been presented [9–15]. Some widely used circuits are full-wave bridge rectifier (FBR) and voltage doubler (VD) [16–18]. In spite of their simplicity and popularity, these circuits suffer from several limitations:

- They consist of diodes, which suffer from forward voltage ($V_f$) loss. Thus, the output voltage and power are low.
- The rectified voltage is unstable.

To overcome these limitations, various strategies have been proposed by researchers in this field. One example is the Bridgeless AC-DC converter proposed by [14] to improve the power flow into the load capacitor and power efficiency. The Bridgeless split capacitor converter circuit is shown in Figure 2a. The MOSFET (Metal Oxide Silicon Field Effect Transistor) switches used in the circuit are operated by an external power supply in both positive and negative half-cycles. This eliminated the problem of losses across the diodes. However, the capacitors C1 and C2 have a large ripple and capacitor C3 has gained steady-state output. Thus, it makes these methods intricate because of the limitation of energy harvester size, losses, and cost [19]. Furthermore, the additional switches can cause switching losses during the switching process. On the other hand, the boost converter, as shown in Figure 2b, with additional switches, results in significant improvement in power conversion from the PD [20]. However, it is rather complex. Power consumption of switches is also higher than the power generated by the PD, rendering it impractical.

A low power stand-alone adaptive circuit was proposed by [21] to maximise power extracted from the PD. It consists of a voltage doubler (VD) and a step-down switching converter. The controller adopted uses PD’s voltage as a feedback signal to improve power extraction. The result shows that the proposed circuit controls the rectified voltage, output power, and efficiency. However, it requires a complex switching circuit and an additional controller circuit. Another approach to maximise output power from PD, namely, the complex conjugate method, has been used in [22]. In this method, the source generator, (i.e., the PD) has a large internal capacitance with a low resonant frequency [23,24]. Therefore,
this method requires a large inductor, in the order of tens to hundreds of Henry, which is impractical [25].

![Figure 2. (a) Bridgeless split capacitor topology-based converter, (b) Boost converter having secondary switches.](image)

Another possible way of maximising power from the PD is to directly attach the PD to the storage device/capacitor. The concept of nonlinear circuits or synchronised switch harvesting on inductor (SSHI) has shown significant improvement in power extracted from the PD. A nonlinear technique was proposed by [26], it demonstrated meticulous power extraction and claimed under similar conditions/excitations the proposed circuit has dramatically improved the extracted power by several hundred percent when compared to the FBR circuit. To implement the switching of SSHI circuits, self-powered SSHI circuits have been proposed in [21,27,28].

Furthermore, the self-powered SSHI was proposed in [29] with some discrete electronic components. The experimental results showed significant improvement in power extraction from PD, which is 1.6 times higher than the FBR circuit. However, the diodes used in the proposed circuits caused a voltage drop in the conversion process. As a result, the conversion losses are higher than the power generated by the PD. In addition, based on the literature, the losses in the switching process are high. Therefore, there is a need to develop a circuit, which offers low losses and constant output voltage. To minimise the forward voltage loss across the diodes, the diode-less circuit was proposed by Maiorca [30] as shown in Figure 3.

![Figure 3. The diode-less circuit.](image)

The study did not show the output power extracted from the proposed circuit. No comparison was made with conventional circuits. Practical application and appropriate electrical boundary condition were also not considered. Arul et al. [31] has shown that the use of MOSFET bridge rectifier circuit, is able to reduce the power loss during the conversion process by minimising the forward voltage loss across the diodes. The MOSFETs used in the circuit are not self-powered. As a result, the switching losses of MOSFETs are high. Consequently, the power loss in switches is higher than the power generated by the PD.

A recent study by Edla et al. [32] improved the above MOSFET bridge rectifier circuit to a self-powered H-Bridge circuit. The proposed circuit was successfully applied for ultra-low voltage and high frequency application. The outcome shows that the proposed circuit notably increases the voltage and the power produced from the PD when compared to traditional FBR circuits. However, this study mainly focused on the rectification process...
at high frequency; its applicability in low frequency and high amplitude human induced excitation is not considered.

So far, much research has been conducted into rectifier circuits for PEH. However, the literature review conducted by the authors also concluded that previous studies mainly adopted a controlled sinusoidal vibration source, usually generated by a mechanical shaker. When human motion is the source of mechanical energy, the AC-DC conversion is more challenging. The AC voltage generated from human motions, such as walking, running, and cycling, is not purely sinusoidal. The generated waveform is often at low frequency, has high amplitude and is relatively unstable due to the complicated nature of such motions [5,33]. A typical AC waveform generated from a PD with a cantilever beam attached to mechanical shaker is shown in Figure 4.

![Figure 4. Voltage generated by piezoelectric device (PD) from walking motion.](image)

Thus far, the suitability of existing rectifier circuits in converting AC voltage generated by PD as a result of low frequency human motion induced non-sinusoidal vibration is unknown. There is thus a need to develop a self-powered rectifier circuit with low losses and capable of providing a stable DC voltage supply under such application.

In this paper, a modified H-Bridge circuit is proposed to convert AC into DC for human motion application, which is an extension of works by Edla et al. [32], Maiorca et al. [30] and Arul et al. [31]. The proposed H-Bridge circuit is a modified version of a typical H-Bridge circuit (which is externally powered by the DC voltage), in which the main components (i.e., MOSFETs) in the circuit are replaced by enhancement type of MOSFETs. In addition, it is a self-powered H-Bridge circuit that does not require an external power supply to trigger the components in the circuit. The rectified DC voltage is expected to be comparatively higher and more stable due to the low threshold voltage ($V_{th}$) of MOSFETs when compared with conventional FBR circuit.

To investigate the conversion capability of the proposed H-Bridge circuit, a series of experimental tests were conducted in this study to compare the performance of the proposed H-Bridge circuit with conventional FBR circuit. AC voltage sources generated by PD attached to a cantilever beam subject to a range of low frequency excitations were considered. Tests were first carried out with a mechanical shaker as a source of controlled, low frequency mechanical vibration. Real-life testings were then conducted with the sources of excitation changed to an adult human performing continuous cycling and walking motions at different speeds.

2. EH Circuits

This section discusses the equivalent circuit modelling of the PD used in the PEH system, followed by a review of conventional circuits, namely, the FBR. The proposed H-Bridge circuit is then introduced.

2.1. Equivalent Circuit of PD

To evaluate the internal characteristics of the given PD, a vibrating PD attached to a cantilever beam with proof mass is shown in Figure 5a. When a typical PD is harmonically
vibrated, it can be modelled as a sinusoidal current source \(i_P(t)\) connected in parallel with its internal capacitance \(C_P\) and resistance \(R_P\) \([31,34–39]\), as shown in Figure 5b. The PD can also be alternatively modelled as a voltage source \(V_P(t)\), as shown in Figure 5c \([21]\).

Figure 5. A vibrating PD (a) excited by mechanical shaker, and its equivalent circuit model as (b) Current source, (c) Voltage source.

A vibrating PD generates an AC voltage that contains both positive and negative half cycles. In both cycles, the internal capacitor of the PD is first charged before the actual power flows out from the PD terminals. The fluctuated characteristics of voltage and current with the mechanical excitation, which contains both positive and negative half cycles is shown in Figure 6. The charging period of the internal capacitor \(u\), denoted as Interval 1 is the non-harvesting period. Interval 2 represents the harvesting period of the PD.

Figure 6. The fluctuated characteristics of current and voltage of a vibrating PD.

The generated current needs to charge and discharge the internal capacitor, as depicted in Figure 5b. During this time, the rectifier circuit is in turn off condition. Thus, there is no output through the circuit, and the external load capacitor \(C_{load}\) does not charge. Interval 1 continues until the magnitude of the PD voltage \(V_P(t)\) equates to the load capacitor voltage. Interval 2 will then begin, and the load capacitor will be charged. A similar process occurs in the negative half cycle.

The generated current by the PD can be expressed as

\[
i_P(t) = \hat{I}_P \sin(\omega t)
\]

where \(\hat{I}_P\) is the magnitude of current, \(\omega\) is the angular frequency, and \(t\) is time. On the other hand, the PD voltage can be expressed as

\[
V_P(t) = V_P \sin \left( \frac{2\pi t}{T_{\text{in}}} \right)
\]

where \(T_{\text{in}}\) is the period of the voltage source, \(V_P\) is the amplitude of the voltage.
2.2. FBR Circuit

When the FBR circuit is connected in parallel with the PD, it charges the load capacitor in 4 modes of operation. A flow chart summarising the modes of operation of FBR circuit in both positive and negative half cycles is shown in Figure 7. The operations in different modes are briefly outlined in Table 1. Further details and explanations are available in the authors’ recent publication [32].

![Figure 7. A flow chart summarising the modes of operation of full bridge rectifier (FBR) circuit in positive and negative half cycles.](image)

Table 1. Four modes of operation of H-Bridge, FBR circuit in positive and negative half cycles.

| Circuit | Positive Half Cycle | Negative Half Cycle |
|---------|---------------------|---------------------|
|         | Mode 1              | Mode 2              | Mode 3              | Mode 4              |
| H-Bridge| When \( t_0 \) < \( t \) ≤ \( t_1 \) | When \( t_1 \) < \( t \) ≤ \( t_2 \) | When \( t_2 \) < \( t \) ≤ \( t_3 \) | When \( t_3 \) < \( t \) ≤ \( t_4 \) |
|         | - Interval 1 begins | - Interval 2 begins | - Interval 1 begins | - Interval 2 begins |
|         | - H-Bridge: OFF     | - MOSFET 1, 4: ON  | - H-Bridge: OFF     | - MOSFET 2, 3: ON  |
|         | - Load capacitor: Not charging | - Load capacitor: Charging | - Load capacitor: Not charging | - Load capacitor: Charging |
| FBR     | When \( t_0 \) < \( t \) ≤ \( t_1 \) | When \( t_1 \) < \( t \) ≤ \( t_2 \) | When \( t_2 \) < \( t \) ≤ \( t_3 \) | When \( t_3 \) < \( t \) ≤ \( t_4 \) |
|         | - Interval 1 begins | - Interval 2 begins | - Interval 1 begins | - Interval 2 begins |
|         | - H-Bridge: OFF     | - D1, D3: ON       | - H-Bridge: OFF     | - D2, D4: ON       |
|         | - Load capacitor: Not charging | - Load capacitor: Charging | - Load capacitor: Not charging | - Load capacitor: Charging |

The power extracted from the FBR circuit \( (P_o(t)) \) varies with the rectified voltage \( (V_{dc}) \) [34]:

\[
P_o(t) = \frac{2 V_{dc}}{\pi} \left( I_p - V_{dc} \omega C_p \right)
\]

(3)

With a load capacitor of low capacitance \( (C_{load}) \), most of the charges from the harvester will flow to the output, but the output voltage is expected to be low and unstable.
2.3. Proposed H-Bridge Rectifier Circuit for PEH in Human Motion Application

The H-Bridge circuit proposed in this study for converting DC voltage from PD excited by low frequency human motion is shown in Figure 8. The H-Bridge circuit was designed using MOSFETs in order to reduce the forward voltage drop suffered by diodes used in conventional rectifier circuits. This leads to lower conversion losses and thus higher power conversion. Another significant advantage of the proposed H-Bridge circuit is its self-powering ability. It does not require an external power to turn on the MOSFETs in the circuit [31]. Therefore, no additional component, like polarity detector and logic gates, is required. As a result, it is also cost effective.

Figure 8. A flow chart summarising the operation of H-Bridge circuit in positive and negative half cycles (1: PMOS, 2: PMOS, 3: NMOS, 4: NMOS; PMOS).

The key difference between the conventional FBR and the H-Bridge circuit is that the FBR circuit comprises of four diodes, while the H-Bridge circuit comprises of four MOSFETs (PMOS: P-Channel MOSFET, NMOS: N-Channel MOSFET). The diodes possess two terminals, namely the anode and the cathode, where the MOSFETs have gate (G), drain (D) and source (S) terminals. The advantage of MOSFET is that the drain to source voltage can be controlled by applying PD voltage on the gate terminal. In addition, the MOSFETs allow flow of current in both directions (D ↔ S) while diodes only allow current in one direction. In addition, each transistor consists of an internal diode is shown in Figure 8, which provides protection against reverse leakage current in reverse bias. The four modes of operation of the H-Bridge circuit in both positive and negative cycles of PD is summarised in Table 1. A flow chart summarising its operation is also presented in Figure 8. Further details and explanations are available in [32].

Notably, the H-Bridge circuit is proven to be more effective than the FBR circuit in AC-DC conversion for PEH at high frequency and low voltage application. In this study, its applicability in human motion induced PEH is investigated. It is anticipated that the use of H-Bridge circuit will improve the output voltage and output power of PD, as well as stabilise the output DC voltage (considering the input voltage AC voltage is not stable), for the sake of charging storage device or powering LED displays.

3. Experimental Design

In this study, the widely adopted [40] cantilever beam with attached PD (resonance frequency: 22.7 Hz) was used as PEH system. Three testing scenarios, namely, shaker test, cycling test and walking test, were considered. The AC voltage generated by PD under all scenarios was rectified by both FBR and H-Bridge circuits. The open circuit (OC) voltage or AC voltage generated by the PD (i.e., the input voltage $V_{in}$ to the circuits), and the corresponding rectified voltage and output power were measured, recorded and analysed. The process of measuring the abovementioned parameters and the equations used for
analysis are described in Section 3.1. The experimental setup and procedures are presented in Section 3.2.

3.1. Measurement of Voltage, Current, and Power of PD

3.1.1. Open-Circuit Voltage

Human motion is a relatively complex motion as the generated peak to peak voltage \( V_{\text{Pk-Pk}} \), or peak voltage \( V_{\text{Pk}} \) is not constant nor purely sinusoidal. Therefore, measuring such PD voltage is difficult, particularly when cycling and walking motions were performed at different speeds. For this reason, the OC voltage of PD was measured using two devices, namely voltmeter (FLUKE 115) and oscilloscope (TBS 1052B):

- When the PD is subjected to external excitation, the positive and negative terminals were connected to a voltmeter. This device measures only the root mean square (RMS) value of the PD voltage. Therefore, the measured RMS voltage was converted into peak voltage \( V_{\text{Pk}} \) by using the Equation (4).

\[
V_{\text{Pk}} = \sqrt{2} \times V_{\text{RMS}}
\]

- To verify the measurement, the peak voltage \( V_{\text{Pk}} \) waveform was observed in the oscilloscope.

In this study, the voltage obtained using both methods is found to be the same.

3.1.2. Current

A vibrating PD can be modelled as a current source or a voltage source [21]. Therefore, the current generated by PD can also be measured in two different ways:

- When the PD is subjected to excitation, the positive and negative terminal was connected to a current meter/ammeter (Type CD771 was used in this study). This device measures the RMS value of the current \( I_{\text{RMS}} \). The measured current can be converted into peak current \( I_{\text{Pk}} \) by using the Equation (5).

\[
I_{\text{Pk}} = \sqrt{2} \times I_{\text{RMS}}
\]

- The current of the PD can also be calculated using the concept of PD equivalent circuit (Figure 5b).

- If the capacitance of the internal capacitor is \( C_P \), and the reactance of internal capacitor is \( X_C \), the peak current flowing through the internal capacitor, \( I_{\text{Pk}} \) is defined as

\[
I_{\text{Pk}} = \omega C_P V_{\text{Pk}}
\]

where \( X_C = \frac{1}{\omega C_P} \). In this study, the current obtained using both methods was found to be the same.

3.1.3. Input Power

- Considering the internal capacitor is in parallel with the PD, the power generated by the PD varies with time. Measuring the constantly changing voltage and current waveforms for evaluation of the AC power is challenging, as Equation (7) is not applicable. Thus, the mean power is a better representation of PD’s power. When PD is subjected to excitation, the voltage and current waveforms are shown in Figure 9.
The power generated by the PD, which is the input power ($P_{in}$) to the rectifier circuit, is calculated as follows:

$$P_{in} = V_{RMS} \cdot I_{RMS} \cdot \cos \theta$$  \hspace{1cm} (7)

where $\theta$ is the phase angle between the voltage and the current of PD.

### 3.1.4. Output Power

The DC voltage and DC current are generally constant. Therefore, the output power of the rectifier circuits ($P_{out}$) is calculated through the product of the voltage across the load capacitor ($V_{dc}$) and the current ($I_{dc}$) through it:

$$P_{out} = V_{dc} \cdot I_{dc}$$  \hspace{1cm} (8)

Note that the above equations were adopted for the calculations and analyses of all testing scenarios considered in this study.

### 3.2. Experimental Setup and Procedures

In this study, a microfiber composite (MFC) patch, (type: M2814-P2, dimension: 37 mm \(	imes\) 17 mm \(	imes\) 0.180 mm, internal capacitance: 30.79 nF) was used as PD in all experimental tests. The MFC patch was attached to the surface of one end of a rectangular aluminium beam (dimension: 205 mm \(	imes\) 20 mm \(	imes\) 1 mm), which was then excited by various sources of excitation. The other end of the cantilever beam carried two permanent magnets, one on the top surface and the other on the bottom surface, as shown in Figure 10. The magnets were configured such that they were attracting each other. Since they were very strong magnets, such configuration resembled firmly attaching a proof mass at the tip of the cantilever. Permanent magnets were used for the convenience of changing tip mass, which changes the resonance frequency of the cantilever beam, as well as the displacement at the free end [39].

![Figure 9. Peak voltage and current waveforms generated by the PD.](image)

![Figure 10. Experimental setup of shaker test.](image)
- FBR circuit with standard forward voltage diodes ($V_f = 0.60\ V$, IN4007).
- H-Bridge circuit with low threshold voltage MOSFETs ($V_{th} = 0.3\ V$, RZR040P01 – PMOS, AP2306AGN – NMOS).

The forward voltage of diodes and the threshold voltage of the MOSFET were checked and verified with a voltmeter. The ensuing output voltage and current were measured by the ammeter, the voltmeter, and the oscilloscope. The input and output power were calculated according to the equations presented in Section 3.1.

### 3.2.1. Shaker Test

The experimental setup of the shaker test is shown in Figure 10. A function generator (Agilent 33210A) was used to deliver a sinusoidal signal to a power amplifier (2706, B & K Agilent), which then amplified the signal before activating the mechanical shaker (APS-113). The shaker generated vibrations according to the input frequency and amplitude to excite the cantilever beam with attached PD.

To simulate common human activities, low excitation frequency [41] (i.e., 1 Hz and 2 Hz) was applied. For each frequency, the amplitude of input voltage (voltage produced by PD) was adjusted to obtain the desired peak OC voltage, from 1 to 5 V. All the input voltages were sequentially applied to both rectifier circuits. The rectified voltage from each circuit was stored in two storage capacitor, namely, C1 and C2. A range of resistances R1, R2, R3, and R4, were also studied for each case. The output power of each circuit was calculated using Equation (8). The ratings of various parameters are summarised in Table 2.

| Scenarios        | Frequency (Hz) | Input Voltage ($V_{in}$) | Rectifier Circuits | Storage Capacitors (µF) | Resistors (kΩ) |
|------------------|----------------|--------------------------|--------------------|-------------------------|----------------|
| Shaker test      | 1, 2           | 1, 2, 3, 4, 5             |                    | C1 = 1                  | R1 = 100       |
|                  |                |                          |                    | C2 = 10                 | R2 = 330       |
|                  |                |                          | H-Bridge FBR       |                         | R3 = 660       |
|                  |                |                          |                    |                         | R4 = 910       |
| Cycling test     | Revolutions per minute (RPM) | 40, 50, 60, 70, 80     |                    |                         |                |
| Walking test     | Speed per hour (km/h) | 1, 2, 3, 4, 5, 6, 7, 8 |                    |                         |                |

### 3.2.2. Cycling Test

In the cycling test, the experimental setup was essentially the same as the shaker test, but the source of excitation was replaced by the leg of a human (male adult weighing 60 kg) performing cycling activity. The PD attached to the cantilever beam was attached to the right leg of the subject, as shown in Figure 11. As mentioned in [42], although there are many movable parts in a human body, the harvester is preferably attached to the leg of a human to maximise the energy harvesting capability.

Measurements were taken for a range of cycling speed, in terms of revolution per minute (RPM), namely 40, 50, 60, 70, and 80 RPM. The voltage produced by the PD was similarly rectified, measured, applied to different resistances (R1, R2, R3, and R4) and stored in a storage capacitor (C1), as summarised in Table 2.

### 3.2.3. Walking Test

In the walking test, the experimental setup was again similar to the other two tests, but the source of excitation was changed to the right leg of the same subject performing walking activity [33] on a treadmill (York-diamond t302). Figure 12 illustrates the treadmill and a snapshot of the subject performing walking motion. Measurements were taken
for a range of walking speed, from 1 to 8 km/h. The rectification process and scenarios considered were the same as the cycling test (summarised in Table 2).

Figure 11. Cycling test.

Figure 12. Experimental setup of a walking test on a treadmill.

4. Results and Discussion

4.1. Shaker Test

4.1.1. Effect of Varying Input Voltage

The rectified voltage through both H-Bridge and FBR circuits (stored in C1) over various input voltage and excitation frequency of 1 Hz and 2 Hz at a resistance of 910 kΩ, is shown in Figure 13a,b, respectively. It can be seen that when the input voltage increases, the rectified voltage through both circuits also increases accordingly. The trend of increase is more consistent in the case of H-Bridge when compared with the FBR circuit. More importantly, the H-Bridge circuit constantly produced higher rectified voltage when compared with the FBR circuit due to its low threshold voltage of MOSFETs.

Another distinct reason for the H-Bridge circuit achieving higher voltage is that the resistance path of MOSFET, which is drain to source, can be controlled with the voltage applied to the gate terminal. When the input voltage on gate terminal is positive, say 1 V (Figure 13) with respect to the source, an electric field is established between the drain to the source (refer to Figure 8). Eventually, induced negative charges in P-substrate forms p-layer below the gate terminal, causing the p-layer to become an induced n-layer. These charges (i.e., electrons) form n− channel in between two n+ regions (one n+ region on drain, the other n+ region on source), which cause the flow of current from drain to source.

If the applied gate voltage is more positive, say 5 V (Figure 13), the induced n− channel becomes deeper and therefore, more current flows from drain to source.
Figure 13. Rectified voltage (stored in C1) versus input voltage through H-Bridge and FBR circuit over varying input voltage at (a) 1 Hz, and (b) 2 Hz at a resistance of 910 kΩ.

This shows that drain to source current is enhanced by the gradual increase of gate voltage. Therefore, when the applied voltage from PD is increasing from 1 to 5 V, the rectified voltage is also increasing accordingly. Another interesting observation is that, by comparing Figure 13a,b, the effect of excitation frequency has a negligible effect on the rectified voltage.

Next, the output power is calculated by Equation (8), and the relationship with input voltage at different frequency is graphically shown in Figure 14. Regardless of excitation frequency and type of circuit, the output power generally increases with an increase in input voltage. Similarly, the output power produced by H-Bridge is considerably higher than the FBR circuit under all input conditions. In addition, it is found that slightly higher output power is achieved at higher frequency (i.e., 2 Hz) because the PD can carry more stable and higher current [43]. This observation is similar for both rectifier circuits.

Figure 14. Output power versus input voltage versus stored in C1 through H-Bridge and FBR circuits at (a) 1 Hz and (b) 2 Hz.

4.1.2. Effect of Varying Rectified Voltage

For the sake of comparison, the rectified voltage (Figure 13) versus the output power (Figure 14) with different resistances (R1–R4) at a constant input voltage of 5 V through both circuits is plotted (Figure 15) in a different form.

It is interesting to find that, for both circuits, the highest output power is achieved with R1, whereas the highest rectified voltage is obtained with R4. The main reason for this is the low current loss/consumption at lower resistance (R1), and the high current loss/consumption at higher resistance (R4), as stated by Ohm’s law. Note that only the
case of input voltage of 5 V is presented, as it corresponds to the highest output power from both circuits. A similar trend is observed with other input voltage (1–4 V) and is herein omitted.

![Figure 15. Rectified voltage (input voltage = 5 V) versus output power through (a) H-Bridge, and (b) FBR circuits.](image)

4.1.3. Effect of Varying Resistance

To further study the performance of the circuits, analysis is carried out by investigating the effect of varying load resistors (R1–R4) on rectified voltage and output power with an input voltage of 5 V. For the purpose of illustration, the outcome obtained with Capacitor C2 is presented. At an excitation frequency of 1 Hz, the rectified voltage by both circuits with different input voltage is plotted against different resistances, as shown in Figure 16.

![Figure 16. Rectified voltage (stored in C2) against resistance at 1 Hz: (a) H-Bridge, (b) FBR circuits with input voltage of 5 V.](image)

From Figure 16, it can be seen that the rectified voltage increases with the increasing resistance, regardless of the type of rectifier circuit. The H-Bridge circuit also consistently provide higher rectified voltage, in comparison with the FBR circuit. The reason is similar to the description provided for Figure 13.

It is found that the rectified voltage in C1 and C2 are similar, so the outcome from C1 is omitted. However, since the capacitance of the C2 is higher than the C1, the subsequently rectified voltage through H-Bridge circuit is found to be more stable than the FBR circuit. However, the charging time of C2 is much longer than C1 due to its large capacitance ratings [18].

Figure 17 demonstrates the output power stored in C2 through both circuits at different resistances (R1–R4) and constant input voltage of 5V. Contrary to the rectified voltage, the trend of output power against resistance is rather different. The output power produced by H-Bridge increases slightly at a lower resistance and remains stagnant at higher resistance. On the other hand, those produced by the FBR circuit show inconsistent trend.
This can be explained by Ohm’s law, where the rectified voltage generally increases with resistance, but the current usually decreases with higher resistance. Thus, the output power achieved through both circuits shows a different trend. Regardless of the resistance, the performance of H-Bridge circuit is once again superior. The output power from H-Bridge circuit is significantly higher than the FBR circuit due to its unique features of MOSFET, which are explained in Section 2.3. Note that the general trend and observation for excitation at 2 Hz is similar to the case of 1 Hz and is herein omitted. The effect of varying frequency is discussed in the following subsection.

4.1.4. Effect of Frequency

Table 3 summarises the rectified voltage and output power achieved by both rectifier circuits with varying input voltage and frequency at a resistance of 910 kΩ. It is evident that the rectified voltage through both circuits at a frequency of 2 Hz is higher than the case of 1 Hz. In addition, the power output from both circuit is also higher in the case of 2 Hz. Two main reasons are attributing to such outcome:

- As frequency increases, the reactance \(X_C\) of the internal capacitance decreases. On the other hand, the current produced by the PD is higher, as shown in Figure 18. Although the generated voltage is adjusted to a fixed value (say 1 V for both 1 Hz and 2 Hz in Table 3), the current generated by the PD at 2 Hz is higher than 1 Hz since the frequency is inversely proportional to time. Thus, the output power at 2 Hz is higher than 1 Hz.

| Input Voltage \(V_{pk}\) | 1  | 2  | 1  | 2  | 1  | 2  | 1  | 2  | 1  | 2  |
|--------------------------|----|----|----|----|----|----|----|----|----|----|
| Frequency (Hz)           | 1  | 2  | 1  | 2  | 1  | 2  | 1  | 2  | 1  | 2  |
|                           |    |    |    |    |    |    |    |    |    |    |
| 1.0                      | 0.49 | 0.41 | 0.26 | 0.53 | 0.10 | 0.25 | 0.16 | 0.28 |
| 1.5                      | 1.38 | 2.09 | 0.45 | 4.2 | 0.18 | 0.41 | 1.91 | 3.79 |
| 2.0                      | 2.35 | 6.07 | 0.49 | 7.2 | 0.24 | 0.43 | 5.83 | 6.77 |
| 2.5                      | 2.81 | 10.0 | 0.73 | 10.70 | 0.58 | 2.08 | 9.42 | 8.62 |
| 3.0                      | 3.41 | 12.8 | 0.96 | 15.2 | 2.3 | 4.98 | 10.5 | 10.22 |

Table 3. Rectified voltage (stored in C2) and output power through both circuits at various frequencies and input voltages with a resistance of 910 kΩ.
As PD’s current increases, the rectified voltage also increases, which leads to increase in output power.

Another important observation is that, regardless of excitation frequency, the H-Bridge circuit consistently produced higher output power than the FBR circuit. This is particularly true when a larger capacitor is used. In conclusion, from Figures 13–18, it is observed that the proposed H-Bridge circuit is capable of producing higher rectified voltage and higher output power under all scenarios. At a frequency of 1 Hz with the input voltage of 5 V, the highest output power attained by the H-Bridge and the FBR circuits are 12.8 µW and 2.30 µW, respectively. Similarly, at a frequency of 2 Hz, the highest output power through the H-Bridge and the FBR circuits are 14.9 µW and 4.98 µW, respectively.

4.1.5. Analysis of Voltage Waveform

To further understand the performance of H-Bridge and FBR circuits, a closer look is taken at the waveform of the rectified voltage. One typical rectified waveform (i.e., a snapshot of the oscilloscope display), at a frequency of 2 Hz with an input voltage of 2 V, is shown in Figure 19.

The red and blue curves represent the voltage rectified by H-Bridge circuit and FBR circuit, respectively. A zoom-in view of the waveform is also presented. It is demonstrated that the voltage rectified by the H-Bridge circuit is not only higher but also more stable than the FBR circuit, as depicted in Figure 19. The use of active diodes (i.e., MOSFET) is relatively straightforward, capable of performing fast switching, having low threshold voltage, and low power consumption. Thus, the voltage rectified by the H-Bridge circuit is more stable.

It is evident that the rectified voltage curve by the FBR circuit is lower when compared with the H-Bridge circuit. The main reasons causing the FBR circuit to yield low rectified voltage is the use of high forward voltage diodes. In fact, the conventional FBR circuit does not turn on unless the generated PD voltage is equal to or higher than the forward voltage of the diodes (i.e., when \( V_f > 0.6 \) V). The key difference between MOSFET in H-Bridge
circuit and diode in FBR circuit is that the MOSFET output can be controlled by increasing the applied gate voltage. In other words, by increasing the gate voltage on the MOSFETs, the resistance path from D ↔ S can be reduced; while in the case of diode, the resistance path from anode to the cathode terminal cannot be reduced. Therefore, the voltage output by the FBR circuit is relatively lower than the H-Bridge circuit. As a result, the power conversion by the FBR circuit is also lower.

It should be noted that the H-Bridge circuit consistently outperformed the FBR counterpart, in which both the rectified voltage and output power produced by H-Bridge circuit is higher than the FBR circuit for all cases. Recalling that the primary intention of this study is to improve the rectified voltage and output power, this is achieved with the use of H-Bridge circuit. In other words, conversion loss is minimised with the use of H-Bridge circuit. In addition, the power loss controlled or saved by the H-Bridge circuit over the FBR circuit is also provided Table 3.

4.2. Cycling Test

4.2.1. Effect of Varying Cycling Speed

In the cycling test, the performance of H-Bridge and FBR circuits is studied when the source of excitation is a person performing cycling motion (Figure 11) at a different speed (RPM). The OC voltage or input voltage (i.e., voltage produced by PD) to both circuits at different cycling speed is shown in Figure 20. It is observed that the voltage produced by PD increases with cycling speed, but due to the complicated nature of human motion, the rate of increase is not very consistent across the different speed.

![Figure 20. Generated input voltage at different speed.](image)

In order to further understand the performance of both circuits, a closer look is taken at the rectified voltage and the output power produced at different cycling speed, as shown in Figure 21. It is evident that regardless of the type of rectifier circuit, both the rectified voltage and power increases with cycling speed. This is due to the fact that, at different cycling speed, the energy input is different and the PD is expected to produce a higher voltage at higher cycling speed (i.e., higher input energy) [44,45].

Similar to the shaker test, both output parameters produced by the H-Bridge circuit is significantly higher than the FBR circuit for all cycling speed. The advantage of the H-Bridge circuit is particularly pronounced at higher cycling speed. At a higher speed, say 70 and 80 RPM, it is noted that the input energy increases disproportionately (Figure 20). However, the rectified voltage and power through the FBR circuit is still limited. The H-Bridge circuit, on the other hand, is able to rectify the voltage and power more efficiently.
4.2.2. Effect of Varying Rectified Voltage

From a different perspective, the output power against the rectified voltage is presented in Figure 22. It is found that, through both circuits, the output power shows a positive correlation with the rectified voltage (implying different cycling speed). In the cycling test, highest output power achieved by H-Bridge and FBR circuit is 10.1 µW and 0.61 µW, respectively, at 80 RPM. In other words, for the same input voltage/energy level, the output power of FBR circuit is only about 6% of the H-Bridge circuit.

4.2.3. Effect of Varying Resistance

Similar to the shaker test, the input voltage from PD was applied to both the H-Bridge and the FBR circuits, with rectified voltage stored in a capacitor and applied to different resistors (R1–R4). Similarly, Equation (8) was used to calculate the output power. The rectified voltage and output power over different resistances at a cycling speed of 80 RPM are shown in Figure 23.

It is observed that the rectified voltage and output power increase with increasing load resistance at constant cycling speed. This observation is in line with the shaker test. Once again, the rectified voltage and output power from H-Bridge circuit is consistently higher when compared with the FBR circuit for all cycling speed and resistance.
4.2.4. Analysis of Voltage Waveform

A typical rectified voltage waveform obtained from the cycling test at 80 RPM is shown in Figure 24. It can be seen that the rectified voltage is not only high in the case of H-Bridge, its rectified waveform is also relatively stable in comparison with the case of FBR circuit. This observation agrees with the shaker test.

![Figure 24. Rectified voltage waveform by H-Bridge and FBR circuits in cycling test at 80 RPM.](image)

4.3. Walking Test

Effect of Varying Walking Speed

In the walking test, the performance of the H-Bridge and FBR circuits is studied with the source of excitation being a person walking on a treadmill at various speed (Table 2). The voltage generated by the PD at a different speed (i.e., the input AC voltage to both circuits) is depicted in Figure 25. Note that at the speed of 1 km/h to 6 km/h, the subject could walk on the treadmill. When the speed reached 7 km/h to 8 km/h, slow jogging motion was performed as walking at such high speed was uncomfortable. It can be seen that the input voltage to both circuits increases with walking speed. However, the rate of increase is not consistent across the different walking speed due to the complicated nature of human walking.

Figure 26 illustrates the relationship of rectified voltage and output power with speed through both H-Bridge and FBR circuits. It is clearly observed that the rectified voltage and output power through H-Bridge is significantly higher than the FBR circuit. This observation is consistent across all three tests. Note that only the highest output parameters obtained are shown in Figure 27 because other scenarios show a similar trend and are therefore omitted.

![Figure 26. The rectified voltage and output power by both circuits at cycling speed of 80 RPM.](image)
Figure 25. Input voltage generated by PD at different walking speed.

Figure 26. (a) Rectified voltage and (b) output power through both circuits in walking test.

Figure 27. Rectified voltage and output power with varying resistances: (a,b) H-Bridge circuit, and (c,d) FBR circuit in walking test.

To further understand the performance of both circuits, the output parameters, namely rectified voltage, output power against different resistances at a speed of 7 km/h and 8 km/h are plotted in Figure 27. Although both circuits are delivering maximum rectified
voltage at high resistance, the H-Bridge circuit once again delivers significantly higher output voltage due to its distinct behaviour of MOSFET, which is explained in Section 2.3.

The output power achieved through both circuits at a speed of 7 and 8 km/h and with a load resistance from R1 to R4 is also demonstrated in Figure 27b,d. It is interesting to find that the output power does not increase proportionately as the rectified voltage with an increase in resistance. With both circuits, the maximum output power is obtained with the use of the smallest resistance, R1 and at the highest speed of 8 km/h. Despite the same excitation, the power produced through H-Bridge circuit is four times of the FBR circuit. A relevant explanation can be found in Section 2.3.

4.4. Comparison of Shaker, Cycling, and Walking Tests

For the sake of comparison, the highest output power achieved by both circuits under three different tests is summarised in Table 4. Across all three tests, maximum output power obtained is 21.05 µW from the walking test with the use of H-Bridge circuit at the highest walking speed. It is also interesting to note that the walking test yielded significantly higher power than the cycling test and shaker test. This is likely to be caused by higher input energy from the large amplitude of walking motion and significant impact energy generated by footstep. Despite the similar frequency, the amplitude of motion in shaker test and cycling test is relatively smaller. In other words, the input energy is lower.

Table 4. Comparison of maximum output power generated by all three tests.

| Testing Scenarios | Sources of Excitation | Controlling Parameters | Rectifier Circuits | Output Power (µW) |
|-------------------|-----------------------|------------------------|--------------------|-------------------|
| Shaker test       | Mechanical shaker     | Frequency: 2 Hz        | H-Bridge           | 15.2              |
|                   |                       |                        | FBR                | 4.9               |
| Cycling test      | Human performing      | Speed: 80 RPM          | H-Bridge           | 10.1              |
|                   | cycling motion        |                        | FBR                | 5.01              |
| Walking test      | Human performing      | Speed: 8 km/h          | H-Bridge           | 21.05             |
|                   | walking motion        |                        | FBR                | 5.01              |

Overall, it is found that the use of H-Bridge consistently produce higher output power and rectified voltage, in comparison with the FBR circuit, regardless of the source of excitation, the capacitor and resistance in use. It is thus confidently concluded that the H-Bridge circuit is superior to the FBR counterpart in rectifying voltage generated by PD under human motion-induced, low frequency excitation.

As stated in [5,42], walking, jogging, and cycling are some of the most common human activities in daily life. In this study, the power generated from such activities performed by an average-sized person is presented. Based on the experimental results, it is observed that the power generated with the use of either rectifier circuits and a range of adopted device [33] is still relatively low when compared with conventional artificial power supply. At this stage, the output power from PD can potentially be used for powering small electronic devices, like LEDs, lighters, piezoelectric microphones, quartz watches, and for charging batteries.

5. Conclusions

In this study, the effectiveness of a proposed H-Bridge circuit in rectifying voltage and power from PEH system under low frequency, human induced excitation is investigated. Based on the experimental results, the use of MOSFETs with low threshold voltage in the H-Bridge circuit has achieved higher rectified voltage and output power in comparison with the conventional FBR circuit. The experimental results have shown that H-Bridge circuit significantly outperforms the FBR circuit under all testing scenarios, namely, shaker, cycling, and walking tests. In the walking test, under the same source of excitation, the proposed H-Bridge circuit produces a maximum rectified voltage of 3.8 V_{dc} and an output power of
21.05 µW, while the FBR circuit yielded 1.6 V_{dc} and 5.01 µW of rectified voltage and output power, respectively. The voltage rectified by H-Bridge also shows higher stability. Thus, it is concluded that H-Bridge is a suitable rectifier circuit for harvesting various human motions induced mechanical energy from PD. For future work, study into dual-stage H-Bridge circuit for human motions application is recommended.

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