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Proceeding Paper

Investigation of the Rectifiers Responses Affecting the Operational Bandwidth in the Electromagnetic Vibration Energy Harvester †

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Abstract: Energy harvesters provide excellent solutions for the power supply problem of wireless sensor nodes (WSNs), and energy harvesters with wider bandwidth will clearly better serve WSNs and assist in the construction of Industry 4.0. Although, the bearing of rectifiers on the load bandwidth of energy harvesters has been rarely investigated. This paper focuses on the impact of diverse rectifiers on the load electrical response of electromagnetic energy harvester in the sweep mode of experiments, especially on the load bandwidth. The rectifiers are set as half-wave rectifier and full-bridge rectifier, respectively, and two different rectifier diodes are adopted in the experiment. The experimental results suggest that the half-wave rectifier exhibits certain advantages especially in the bandwidth field. If a full-bridge rectifier using high-speed switching diodes is replaced with a half-wave rectifier using Schottky diodes under the load resistance of 100 Ω, the load bandwidth will be increased by almost 1.9 times. At length, a preliminary analysis of the experimental results is provided.

Keywords: rectifiers; diode; vibration energy harvesting; wireless sensor nodes

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1. Introduction

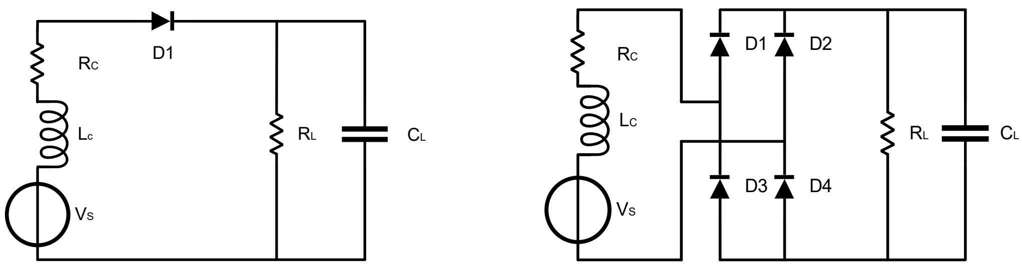
Wireless sensor nodes (WSNs), as an emerging miniaturized intelligent device, have received widespread attention due to their ability to monitor the health of industrial equipment structures [1]. One of the important factors limiting the large-scale application of WSNs is power supply, and vibration energy harvesters (VEHs) provide suitable solutions to avoid the inconvenience caused by battery applications. Among various VEHs, electromagnetic vibration energy harvesters (EMVEHs) that can collect the energy generated by human body or destination equipment vibration are eye-catching, with the advantage of simple structure that facilitates large-scale manufacturing [2–4]. Meanwhile, the rectifier, as a crucial module, plays a pivotal role in the energy harvesting system. It can convert the mechanical energy generated by vibration into AC power, and further convert AC power into DC power that can be used to power the load through a rectifier [5–8]. It is self-evident that as a major module of the energy harvester system, the rectifier will inevitably have a significant impact on the electrical parameters of the load, which is worthy of in-depth investigation and analysis.

The half-wave rectifier composed of single diode and the full-bridge rectifier composed of four diodes (H-bridge) are the two most frequently adopted rectifiers in the field of power electronics. Based on these two rectifiers, a wide variety of advanced rectifiers have been derived for energy harvesters. However, for low-power harvesters, the complex structure of advanced rectifiers means that the proportion of energy loss in the circuit will be significant, and the sophisticated control strategy will inevitably lead to an increase in cost. Therefore, advanced rectifiers will not be discussed here. Half-wave rectifiers are usually at a disadvantage in competition with full-bridge rectifiers due to their inability to harvest half of the AC energy. The existing energy harvester circuits involving rectifiers often take the power of the load and the electromechanical conversion efficiency of the system as evaluation points. Research results have shown that half-wave rectifiers can also occupy a place in low-power energy harvesting systems, but the evaluation of bandwidth as a parameter has not been mentioned [9]. A wider bandwidth signifies that the harvester will be able to deliver more electrical energy to the load within a larger applied frequency range. Therefore, this paper compares the responses of half-wave rectifiers and full-bridge rectifiers applied to EMVEH from multiple perspectives, especially bandwidth, through experiments.

2. Methodology

2.1. Governing Equations

Here, WSNs can be simplified as a pure load resistor without parasitic parameters, and the electrical parameters of the load resistor are of concern. The primary link is to establish a circuit model of the harvester containing a half-wave rectifier and a circuit model of the harvester with a full-bridge rectifier, as shown in Figure 1.



(**a**) (**b**)

Figure 1. (**a**) Circuit model of the EMVEH containing a half-wave rectifier; (**b**) Circuit model of the EMVEH containing a full-bridge rectifier.

In the circuit model, R_c and L_c represent coil resistance and coil inductance, respectively, while D_1 to D_4 represent rectifier diodes. R_L is the load resistor, and in parallel with it is the filter capacitor C_L. As a sinusoidal voltage source, V_s is used to characterize the electrical output parameters of EMVEH, attributed to the conversion relationship between mechanical and electrical domains. Here, the performance of the load in the frequency domain is investigated, so the expression for V_s can be given as:

$$V_s = 4Nbl_c^2 c_f x\omega \quad (1)$$

where N is turn number of the coil, b is the average magnetic flux density, l_c is the standard diameter of the coil, c_f is the coil filling coefficient, x represents the coil displacement, and ω represents the applied frequency [4,10]. By listing a set of node voltage equations, the voltage value of the load resistor in the frequency domain can be obtained. It should be noted that diode typically considered constant voltage drop here need to be considered as a series combination of an equivalent resistor R_d and a voltage source V_d. Therefore, the voltage of the load resistor in half-wave circuit can be expressed as:

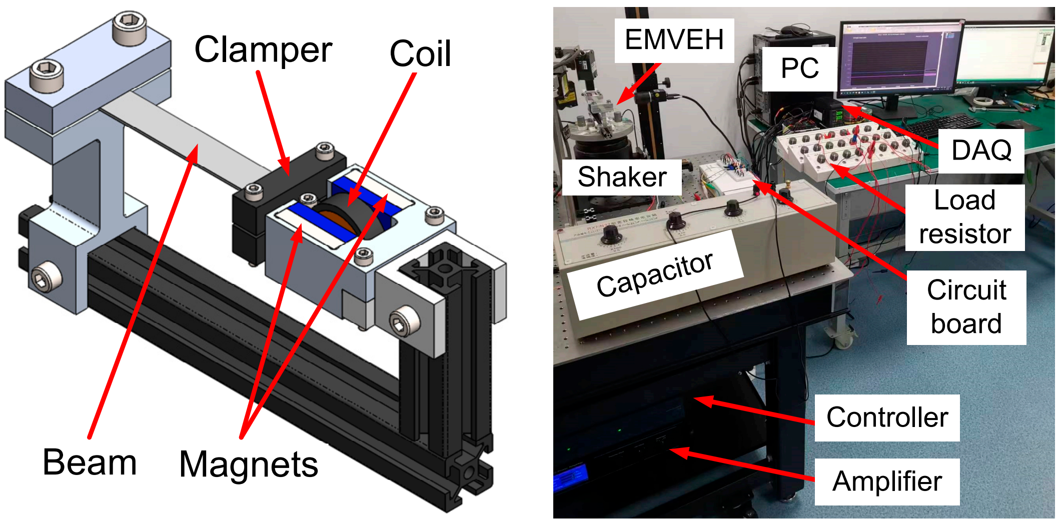
$$V_{half}(\omega) = \frac{R_L(V_s - V_d)}{(1 + j\omega R_c C_L)(R_c + j\omega L_c + R_d) + R_L} \quad (2)$$

where $j^2 = 1$. For a full-bridge rectifier circuit, the difference between it and a half-wave rectifier circuit in the frequency domain is that there are two diodes running in each half cycle. Therefore, the expression for the voltage of the load resistor in a full-bridge rectifier circuit is:

$$V_{full}(\omega) = \frac{R_L(V_s - 2V_d)}{(1 + j\omega R_c C_L)(R_c + j\omega L_c + 2R_d) + R_L} \quad (3)$$

2.2. Experimental Setup

A single-degree-of-freedom cantilever beam EMVEH is used for experiments, as shown in Figure 2a. The free end of the cantilever beam has coil mass, while the other end is fixed on a bracket. When the harvester is forced to undergo harmonic vibration, the coil will cut the magnetic induction line regularly, generating sinusoidal AC power under the domination Faraday's electromagnetic induction law. Figure 2b reveals the overall experimental system setup, including the MS-50 shaker, DR08 resistor box, RX7/N37 precision capacitor box, and NR HA-08 data acquisition (DAQ) card.



(**a**) (**b**)

Figure 2. (**a**) SDOF electromagnetic energy harvester; (**b**) Overall experimental system setup.

By inputting the correct control instructions on the PC, the shaker can be given a preset acceleration with the assistance of the controller and amplifier, while the probe from DAQ card is connected to both ends of the load resistor to obtain voltage data. Some key parameters related to the experiments can be seen in Table 1.

Table 1. Key parameter settings related to the experiment.

Descriptions	Parameters
Acceleration	0.1 g
Beam length	77 mm
Beam width	12.7 mm
Beam thickness	1 mm
Coil turns	570
Coil resistance	7.6 Ω
Coil inductance	4.7 mH

Filter capacitor	470 μF

The examination of the bandwidth and maximum power of the load resistor led to the adoption of the sweep mode (18–21 Hz) in this experiment, with the resistor values ranging from 100 to 800 Ω in steps of 100 Ω. The generally used high speed switching diode 1N4148 and Schottky diode MBR745 are both considered in experiments to identify the impact of different rectifier diode models on responses.

3. Results and Analysis

For basic half-wave circuits and full-bridge circuits, it is difficult to avoid the occurrence of ripples in the load-voltage curves at relatively low frequencies, which to some extent may cause interference in the investigation of the parameters of concern. Therefore, it is imperative to filter the voltage-frequency curve, which means it is necessary to convert the generated sawtooth waves into relatively smooth waves for comparison and analysis. Figure 3 demonstrates the voltage-frequency curves under multiple load resistors, rectifiers, and types of rectifier diodes.

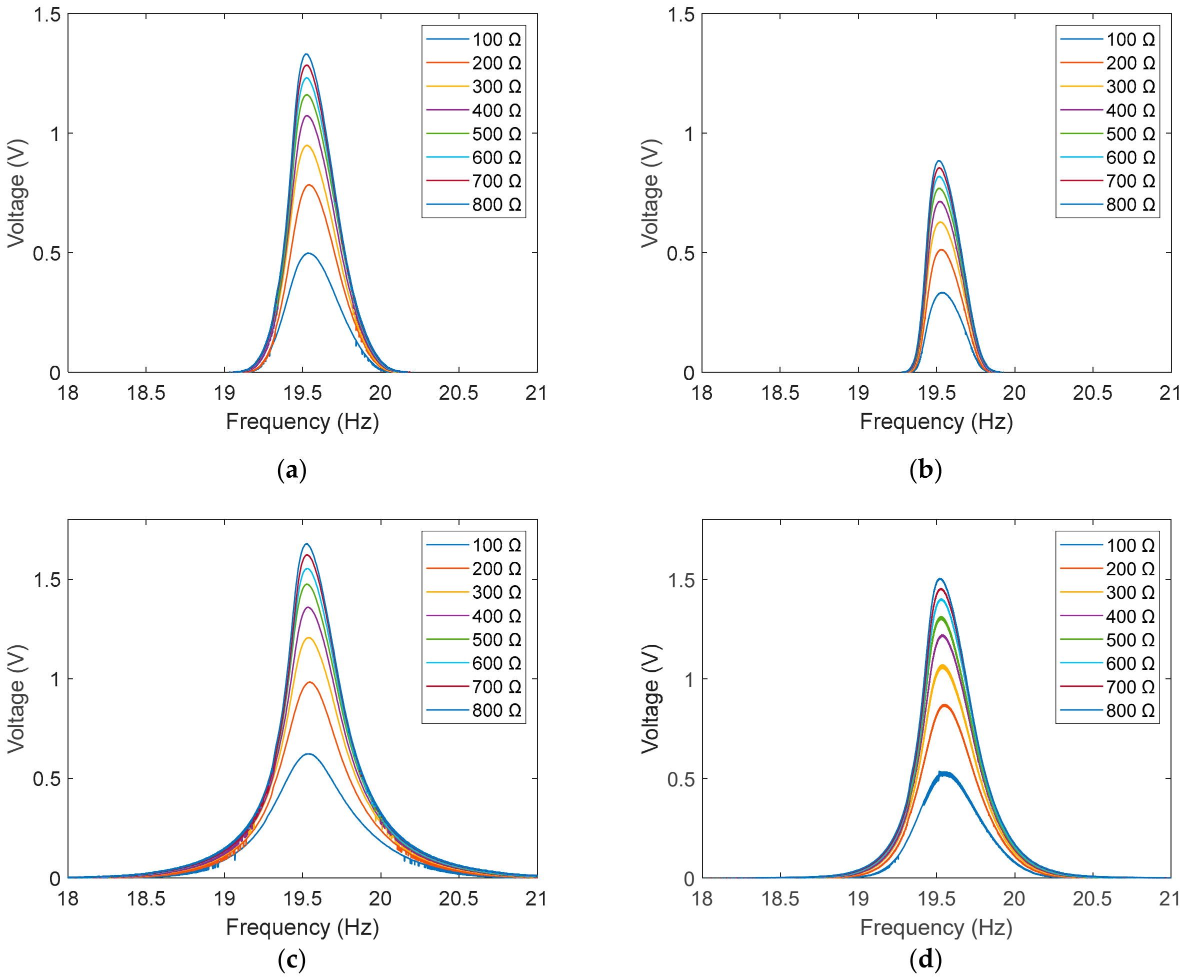


Figure 3. Performances of load voltage versus frequency under different load resistors: (**a**) Half-wave circuit using 1N4148 diodes; (**b**) Full-bridge circuit using 1N4148 diodes; (**c**) Half-wave circuit using MBR745 diodes; (**d**) Full-bridge circuit using MBR745 diodes.

From Figure 3, it can be preliminarily observed that diverse load resistor values, circuit structures, and rectifier diode models have no effect on the resonant frequency of these load resistors, which undoubtedly paves the way for obtaining the maximum voltage point in these load voltage-frequency curves. Once the load voltage and load resistance values are known, the power of the load can be obtained according to the methods in circuit theory. Moreover, the bandwidth of each curve can be derived from the maximum voltage point. Table 2 declares the maximum load power value and bandwidth of each curve obtained from the experiment.

Table 2. Peak power and bandwidth performance of load resistors under distinct circuits in the experiment.

Load Resistance (Ω)	1N4148				MBR745			
	Have-Wave		Full-Bridge		Have-Wave		Full-Bridge	
	Peak Power (mW)	Bandwidth (Hz)	Peak Power (mW)	Bandwidth (Hz)	Peak Power (mW)	Bandwidth (Hz)	Peak Power (mW)	Bandwidth (Hz)
100	2.48	**0.27**	1.11	0.19	3.88	**0.36**	2.86	0.30
200	3.08	**0.25**	1.31	0.18	4.83	**0.31**	3.78	0.27
300	3.00	**0.24**	1.32	0.19	4.85	**0.29**	3.81	0.27
400	2.88	**0.24**	1.28	0.18	4.62	**0.28**	3.72	0.26
500	2.70	**0.24**	1.18	0.19	4.35	**0.28**	3.44	0.25
600	2.53	**0.23**	1.12	0.18	4.02	**0.27**	3.26	0.25
700	2.36	**0.23**	1.05	0.18	3.76	**0.27**	3.01	0.25
800	2.21	**0.23**	0.98	0.18	3.52	**0.27**	2.83	0.25

The experimental results indicate that the curves plotted from the experimental data exhibit some similarities. In each case, as the value of the load resistor increases, the load voltage reveals an upward trend, but the growth rate gradually decreases, resulting in a trend of first increasing and then decreasing in the variation of load power. It is worth noting that these changing trends are not only applicable to circuits containing half-wave rectifiers, but also to circuits with full-bridge rectifiers, and are independent of the type of rectifier diode adopted. Simultaneously, the increment in the value of the load resistor results in a slight decrease in the bandwidth of the load voltage-frequency curve in each case, although this shift is slight relative to the change in the load voltage value.

Certainly, diverse voltage-frequency curves also exhibit noticeable differences. Under each set of load resistor values, if the ripple coefficient is not evaluated, the support of the half-wave rectifier will enable the load resistor to exhibit greater advantages, that is, compared to the load in a full-bridge circuit under the same conditions, the load served by the half-wave rectifier can harvest more energy, occupy larger peak power and wider bandwidth. Here, in order to better investigate the impact of rectifiers on load bandwidth, the bandwidth ratio can be defined as the ratio of load bandwidth in half-wave rectifier circuit to that in a full-bridge rectifier circuit. Select the case where the load resistance value is 100 Ω. If the rectifier diodes in the harvester circuit are Schottky diodes, the bandwidth ratio is 1.2. If the model of the rectifier diode is set to 1N4148, the half-wave rectifier brings visible advantages to the load bandwidth, with a bandwidth ratio of 1.42. Obviously, regardless of the rectifier diode type, the half-wave rectifier provides better service for the load in the bandwidth field. Reviewing the experimental data, it can be observed that as the load resistance increases, the bandwidth ratio shows a falling tendency. Compared to high-speed switching diodes, Schottky diodes should be selected and placed in energy harvester circuits. The presence of Schottky diodes will broaden the bandwidth of the voltage frequency curve under other conditions that are consistent. Still considering the case where the load resistance value is 100 Ω, if a half-wave rectifier is used in the circuit, the operation of the Schottky diodes will result in a curve bandwidth of 1.33 times that of 1N4148 diodes when they are adopted, and this multiple in the full-bridge rectifier circuit reaches 1.58. If a half wave rectifier using MBR745 diodes is replaced by a full bridge rectifier using 1N4148 diodes, the load bandwidth will be dramatically increased by 1.9 times.

For EMVEHs with tiny harvesting power, the diode loss is significant, so the fewer diodes in half-wave rectifiers has become a key factor in this load bandwidth evaluation competition that outperforms full-bridge rectifiers. Meanwhile, the superiorities brought by Schottky diodes for load bandwidth transmit new evidence for the necessity of their promotion. Nevertheless, in addition to peak power and bandwidth, the energy harvesting interface circuit for WSNs should also consider other factors such as ripple coefficient and power factor. Therefore, balancing the pros and cons among multiple electrical parameters is a challenge that harvester circuit designers must face.

4. Conclusions

The investigation of rectifiers responses based on electromagnetic energy harvesters reveals the advantages that half-wave rectifiers can bring to the load in term of bandwidth compared to full-bridge rectifiers, which has been perspectives that few researchers have previously focused. The merit of certain harvesters containing half-wave rectifiers in providing power to WSNs needs to be made a profound study. Schottky diodes are prominent electronic components as rectifier diodes for low-power harvesters, otherwise peak power and bandwidth will be unnecessarily reduced.

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