Journal of Physics:
Conference Series

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To cite this article: M S A Yazib *et al* 2023 *J. Phys.: Conf. Ser.* **2550** 012006

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Comparative study of vibration energy harvesting on home appliances using piezoelectric energy harvester

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Abstract. This project was developed to harvest vibration energy using a piezoelectric energy harvester. The availability of home appliance vibration energy is a promising solution to get clean energy resources to manipulate wasted energy. When the appliances' vibration hits the piezoelectric energy harvester surface, pressure is applied to the piezoelectric transducers and converts mechanical energy into electrical energy. The piezoelectric energy harvester's efficiency depends on the availability of the home appliances' vibration energy; thus, using multiple piezoelectric transducers in series generates more power. The piezoelectric' alternating current (AC) output is fed to a Cockroft-Walton voltage multiplier (CWVM) to convert into direct current (DC) and boost the output. Four piezoelectric transducers connected in series have successfully produced a voltage of up to 4.7 V. Its output voltage can be harnessed to power low-voltage electronic devices.

1. Introduction

Energy harvesting techniques are a method of generating electricity by capturing energy from one or more nearby energy sources. The energy harvesting techniques used nowadays include thermoelectric, photovoltaic, piezoelectric, pyroelectric, wireless or electromagnetic, wind and vibration. Over the last decade, there has been an increase in research on power harvesting technology [1–3]. Waste energy can be harvested to generate electricity, which can be utilised to power low-power devices. This study has been focusing on vibration energy as an energy resource. With this piezoelectric technology, vibration energy may be transformed into electrical energy. By converting mechanical energy (vibration) to electrical energy, the piezoelectric can generate alternating current (AC). However, the amount of energy produced by vibration is low and not stable.

According to [4], most piezoelectric electricity sources produce small power in milliwatts and are unsuitable for application in the system. However, it is suitable for small a device. One proposal is that they are used for micro-scale devices, such as in a device harvesting micro-hydraulic energy. Motion from humans, vibration in low frequency and acoustic noise is the example of mechanical strain. Nevertheless, as piezoelectric produces AC voltage and requires time-varying inputs, mechanical movement is more efficient.

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2. Literature review

2.1. Energy harvesting

All processes that involve energy conversion are inefficient. For example, motors get hot, as do power transistors, automobile engines, and light bulbs; energy is wasted as heat [5]. By converting part of this lost energy to power, energy collecting devices may put it to use. Energy harvesting technology can potentially replace batteries in some applications with proper design. The best-known energy harvesting collectors are large solar panels and wind generators, which have become primary alternative energy sources for the power grid. However, small, embedded devices depend on energy scavenging systems that can absorb milliwatts of energy from thermal, biological, mechanical, optical, and vibration sources. Numerous energy-collecting devices are now in use, and several cutting-edge methods are on the horizon. Light, heat, vibration, and RF are the most now-common energy sources.

2.2. Kinetic energy source and piezoelectricity energy

In this research, one paramount issue is identifying electrical appliances that produce appropriate vibration or kinetic energy that can be harvested. In physics, an object's kinetic energy is the energy it possesses due to its motion [6]. Kinetic energy is an object's movement energy, and home electrical appliances' vibrations fit this category. Appliances such as washing machines, food processors and massage chairs produce sufficient vibration while operating, albeit with different intensities. In addition, vibration can be transferred between objects and converted into electrical energy.

A piezoelectric transducer is an electroacoustic transducer that can convert mechanical force or pressure into electrical energy. These transducers can produce easily quantifiable values, i.e., output voltage, that can be measured easily using a multi-meter compared to other physical quantities, such as pressure, stress, and force, as these quantities cannot be calculated directly [7].

The phrase piezoelectricity, derived from the Greek word 'piezien' for "squeeze or press", refers to the ability of piezoelectric materials to produce an electric field when a mechanical force is applied, a phenomenon known as the direct piezoelectric effect [8]. Briscoe and Dunn defined piezoelectricity as "electric charge that builds up in materials with non-centrosymmetric crystal structures in response to mechanical stress" [9]. A non-centrosymmetric structure is a crystal property with no point reflection or a centre of similarity that enables electrical charges to accumulate.

On the other hand, it was described by Erturk and Inman as "a sort of connection between the mechanical and electrical behaviours of ceramics and crystals belonging to particular classes" [10]. It has a reversible linear interaction between the mechanical and the electrical states because piezoelectric material will produce electricity when pressure is applied. Conversely, it will be physically deformed if electricity is applied as illustrated in figure 1. This property makes piezoelectric useful in generating ultrasound waves.

Piezoelectric generates electrical power by converting vibration source, sound wave, or mechanical stress into an AC source using ceramic that exhibits the piezoelectric effect. The piezoelectric phenomenon was discovered in 1880 by Pierre and Jacques Curie [11]. The piezoelectric effect is a process where a piezo crystal converts vibration energy into electricity. Inside the piezoelectric crystal, there is a polarity [12]. This piezo has two polarities: a positive charge and a negative charge, known as protons and electrons. It is also known as an electrical charge. They are isolated but symmetrically distributed. Hence, the piezo crystal is electrically neutral and has equal numbers of positive and negative charges. The electric dipole forms at each of the protons and the negative charge. A dipole is a pair of equal and oppositely charged or magnetized poles detached by distance. The regions where the dipoles are near each other tend to be aligned and are called Weiss domains.

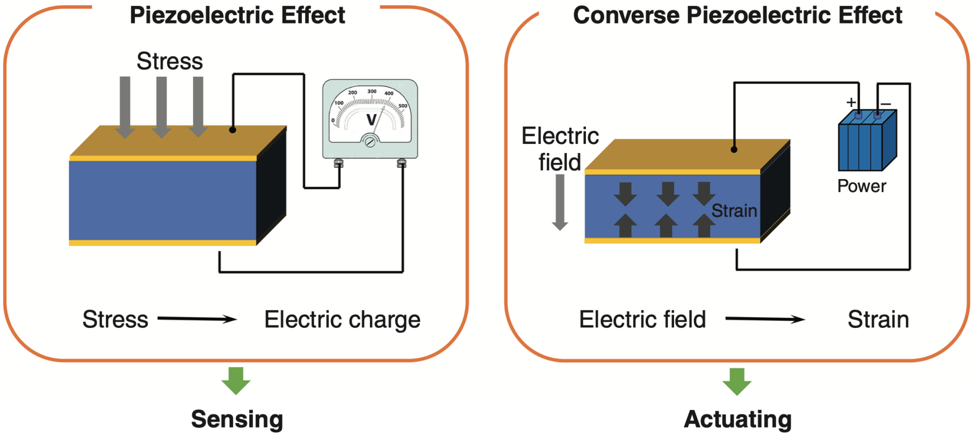


Figure 1: Conversion from stress or pressure into electricity in sensing mode and vice versa in actuating mode [13].

2.3. Cockroft-Walton voltage multiplier

The Cockcroft-Walton voltage multiplier (CWVM) is a voltage multiplier that converts an AC or pulsing DC electrical source from a low voltage level to a higher DC voltage level. To produce high voltages, it consists of a voltage multiplier ladder network of capacitors and diodes, as shown in figure 2. Contrary to transformers, this approach does not call for a hefty core or a substantial amount of insulation or potting [14]. Using only capacitors and diodes in a cascading network, CWVM converts relatively low AC and steps up to high DC values while at the same time being far lighter and cheaper than transformers or other voltage multipliers. As a result, the CWVM is a highly sophisticated high voltage production method that can quickly be employed in a lab setting.

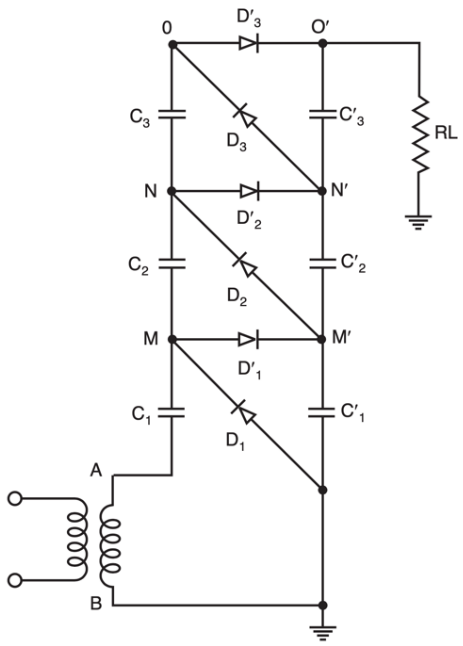


Figure 2: A three-stage single-phase cascade circuit of the Cockroft-Walton voltage multiplier [15].

3. Problem statement

Some appliances in the house produce vibration. Through the vibration, kinetic energy is produced. Most equipment that produces vibration will have a moving part, such as motors. The use of motors will result in a large amount of electrical energy consumption, increasing the electrical bills. Thus, a considerable waste of energy occurs because the kinetic energy from the vibration is not used. Alternative methods should be used to ensure there is less energy wastage and thus ensure that clean energy is used optimally in home appliances. Since this kinetic energy is readily available around the house, the application of piezoelectric transducers is appropriate.

Therefore, a converter circuit is necessary to optimise the output from piezoelectric, such as a rectifier, integrated circuit, voltage doubler or voltage multiplier. This research will focus on the input configuration of the energy harvester that is integrated with Cockcroft-Walton voltage multiplier circuit that will be used to harvest energy on home appliances. The circuit should be able to increase the small AC voltage input to the designated voltage.

4. Methodology

4.1. Project development

Figure 3 shows the block diagram of the vibration energy harvesting process. There are four main parts, which are home appliances, piezoelectric sensor/transducer, voltage multiplier and load. Five home appliances which are the washing machine, laundry dryer, food processor, vacuum cleaner and speaker are chosen as the primary source of vibration energy. The AC voltage generated by the piezoelectric transducer is converted and multiplied using CWVM.

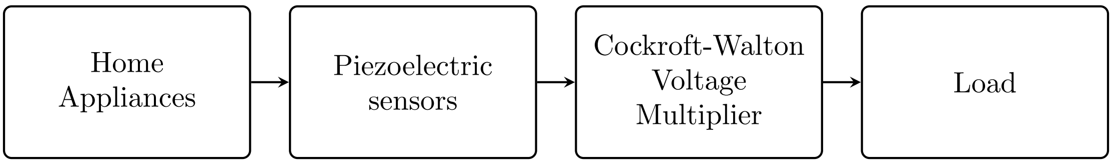


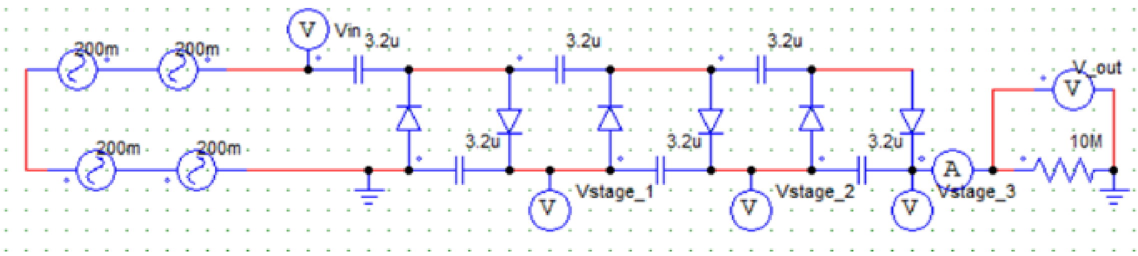
Figure 3: Vibration energy harvesting block diagram.

The piezoelectric tile is built from a set of circular piezoceramic elements used to detect the stress and pressure of human footsteps. Moreover, it has better efficiency than other piezoelectric materials, such as polyvinylidene fluoride (PVDF). Remarkably, it can convert 80% of kinetic energy into electricity. Besides, the output voltage of the piezoelectric transducer is higher and more consistent during energy conversion compared to PVDF. The piezo model being used is PAX116, and its diameter is 35 mm. Before selecting this piezo material, it is necessary to consider the energy to power low-voltage and low-energy electronics appliances. The rating of the resonant frequency of this piezo is 2.8 kHz. The higher the resonant frequency, the piezo would be able to generate more energy.

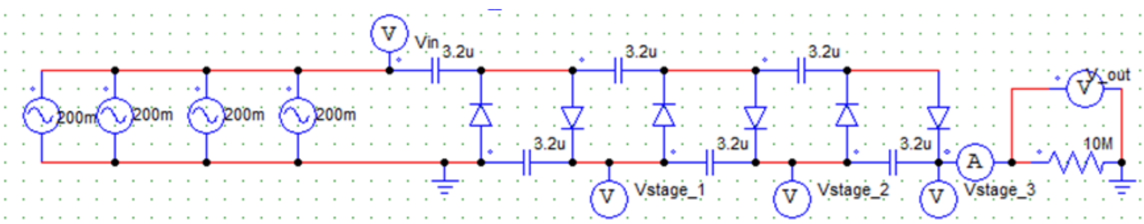
4.2. Circuit construction

In the circuit simulation, the main objective is to achieve the desired voltage output by multiplying the input. The selected CWVM circuit is also called a cascaded voltage multiplier. For the input, four piezoelectric transducers are connected in three different configurations. Figure 4a shows four piezoelectric transducers connected in series, while figure 4b and figure 4c illustrate parallel and series-parallel connections, respectively. For simplicity, a 200 mV_{rms} AC source is chosen as a substitute for the piezoelectric transducer as an input and 1N40007 diode is used as rectifiers. The substitution value is obtained from a measurement of a single press of the transducer. Table 1 shows that, as the stage increases, the voltage at each stage is multiplied.

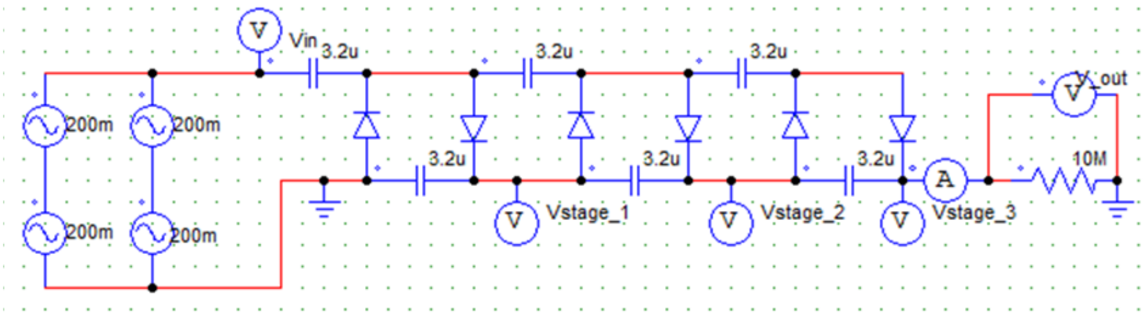
The input voltage is multiplied by the number of stages of CMVW. The input voltage for the series connection produces the highest output voltage followed by the series-parallel and the lowest is the parallel connection. Thus, the project is going forward with the series configuration for the input connection.



(a) Series connection.



(b) Parallel connection.



(c) Series-parallel connection.

Figure 4: Piezoelectric input connections with CWVM.

Table 1: Measured output at each stage for three different input configurations.

	Input voltage	Output voltage (V)		
Configurations	V_{in} (mV)	V_{stage_1}	V_{stage_2}	V_{stage_3}
Parallel	200	0.378	0.755	1.132
Series	800	1.529	3.051	4.571
Series-parallel	400	0.762	1.524	2.284

5. Results and discussion

Other than the initial experiment of a single piezoelectric, five types of home appliances have been chosen as the potential source of vibration. The appliances are a washing machine, laundry dryer, food processor, vacuum cleaner, and audio speaker. Figure 5 shows that the piezoelectric harvester consists of 4 pieces of piezoelectric transducers with a diameter of 30 mm connected in series with the CWVM circuit. Another set of two transducers connected in series complete with its own CWVM are also present during the experiment for comparison purposes. The piezo surface should be attached evenly to the appliances surface to achieve maximum efficiency in collecting the vibration energy.

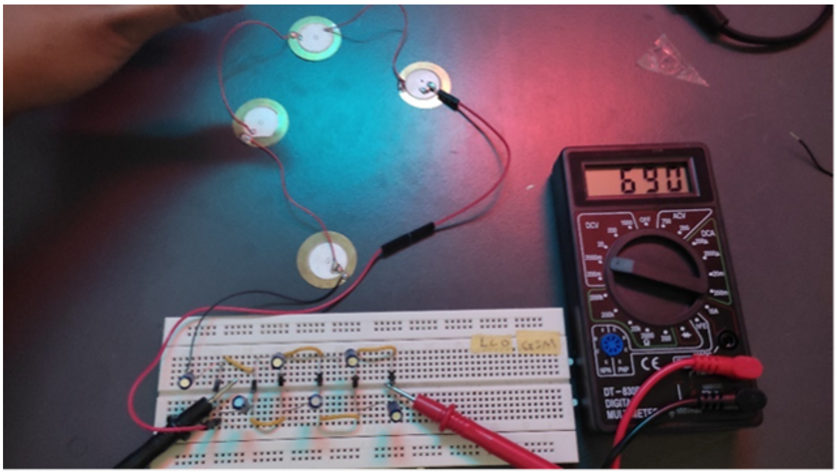


Figure 5: Piezoelectric harvester configuration using four piezoelectric transducers connected in series.

Table 2: Output voltage harvested from the appliances generated by two and four piezoelectric transducers connected in series with the CWVM.

	Washing machine (V)		Laundry dryer (V)		Food processor (V)		Vacuum cleaner (V)		Audio speaker (V)	
Time (s)	2	4	2	4	2	4	2	4	2	4
30	0.147	0.305	0.247	0.405	0.213	0.490	0.290	0.580	0.138	0.221
60	0.453	1.022	0.593	1.172	0.603	1.282	0.573	1.482	0.352	0.582
90	0.722	2.023	0.718	2.121	0.822	2.381	1.573	2.581	0.773	1.681
120	1.098	2.628	0.998	2.976	1.213	2.998	1.696	3.512	1.025	2.512
150	1.398	3.516	1.477	3.311	1.479	3.475	1.877	3.988	1.248	3.258
180	1.836	4.237	1.936	4.381	2.007	4.557	2.215	4.717	1.614	3.875

Table 2 shows the voltage output generated by the transducers harvesting the vibration energy of the home appliances. Naturally, the more transducers connected as the input, the higher the output voltage is generated, as seen from the results of two versus four transducers from each home appliance. Besides, the characteristic of CWVM can be seen clearly; the input voltage is multiplied by stages, and it takes more time to charge each capacitor.

Table 3: Current and voltage output generated at 180 seconds by two and four piezoelectric transducers and the calculated power output.

	Voltage (V)		Current (A)		Power (W)	
Appliances	2	4	2	4	2	4
Washing machine	1.836	4.237	0.170	0.336	0.312	1.424
Laundry dryer	1.936	4.381	0.180	0.358	0.348	1.568
Food processor	2.007	4.557	0.201	0.403	0.403	1.836
Vacuum cleaner	2.215	4.717	0.221	0.419	0.490	1.976
Audio speaker	1.614	3.875	0.161	0.320	0.260	1.240

The power harvested from the vacuum cleaner is the highest compared to the rest of the appliances as seen in table 3. It is because even though the vacuum cleaner has the smallest size in comparison, it produces a much higher vibration frequency and affects the harvested energy. It is further proved by the voltage generated by the food processor and the audio speaker. The fast-spinning of the food processor motor produces a steady, high-vibrating frequency. On the other hand, the audio frequency from the speaker is too varied to create an excellent constant vibration for the harvester. Another factor impacting the energy harvested is the piezoelectric transducers' positioning and the way it is secured. For example, a poorly located transducer, far away from the vibration source, might not be able to thoroughly pick up the vibrations, thus lowering the voltage output.

6. Conclusion

In conclusion, home appliances' waste of kinetic energy in the form of vibration can be harvested using a piezoelectric transducer. Each home appliance produces varying amounts of vibrations. It proves that the mechanical energy from the vibrations can be converted into electrical energy. A set of four transducers connected in series to the CWVM can produce nearly 5 V of output voltage when being used to harvest from the appliances. Increasing the number of transducers connected in series or increasing the number of the CWVM stages will boost the output voltage. Many low-voltage electronic devices, especially IoT, can benefit from the harvested power.

Acknowledgments

The authors would like to thank the Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis (UniMAP), for providing the facilities and financial support under FKTE Research Ativities Fund.

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