SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Harvesting Energy from Rainfall: Initial Study by Exploring Diverse Piezoelectric Array Configurations for Enhanced Electricity Generation in Proteus Software

Siti Nurlina Noor Azmi[1], Suriana Salimin[1,*]

[1] Green and Sustainable Energy Focus Group (GSEnergy), Faculty of Electrical and Electronic Engineering, UTHM, Parit Raja, Batu Pahat, Johor, Malaysia

ARTICLE INFO

Article history:
Received 18 May 2024
Received in revised form 9 July 2024
Accepted 20 July 2024
Available online 30 August 2024

Keywords:
Piezoelectric technology; rainfall; array configuration; proteus software

ABSTRACT

This paper presents an innovative approach to designing and analyzing a simulated piezoelectric energy harvesting system for electricity generation by employing various array connections using Proteus software. The ingenious concept of harnessing energy from rainfall through piezoelectric technology has become an exciting way to turn a common natural occurrence into a possible power source. Rainfall energy harvesting introduces a novel approach that capitalizes on the mechanical energy imparted by raindrops as they strike surfaces, such as rooftops, pavements, or specially designed structures. This study explores distinct piezoelectric connection types to determine their impact on output voltage, focusing on applications such as rechargeable batteries and LEDs. The system begins by harvesting vibration and applying it to the piezoelectric disc. The investigation prioritizes identifying the optimal array connection design. Array configurations of series (S), parallel (P), and combination of series-parallel (SP) are assessed in the simulation. Notably, the series connection of 10 units of piezoelectric elements yielded the highest output voltage of 8.5V. The findings provide valuable insights into finding the optimal array connections in enhancing piezoelectric electricity generation. This research contributes to the initial study and development of potential piezoelectric energy harvesting system from rainfall, offering insights into a greener and more self-sufficient energy future.

1. Introduction

In developing nations, there is a common presence of favourable renewable resource endowments, a swiftly expanding demand, and a noticeable absence of traditional legacy generation systems. As the costs of wind and solar power fall below those of non-renewable alternatives, these developing countries are primed for a rapid adoption of variable renewable energy systems [1]. The primary energy sources used in dispatchable generation include generation from coal, nuclear, hydropower, diesel, and natural gas plants. These sources can store some amount of the primary

* *Corresponding author.*
E-mail address: suriana@uthm.edu.my

https://doi.org/10.37934/aram.123.1.4455

energy source on site and then generate electricity to meet demand needs. One key feature of these conventional sources is the use of synchronous generators as the point of connection to the electrical power system. A synchronous generator is used to develop a 50 or 60 Hz alternating current (AC) waveform of electricity. Over a century ago, AC was selected as the favoured approach for generating and transporting electricity primarily due to its capacity to transmit power over extended distances using exceptionally high voltages and relatively modest current levels [2]. In order to achieve various renewable electricity against the rising of electricity demand, it is crucial to maintain the flexibility and reliability of electricity generation.

Piezoelectricity is a combination of the two words, “piezo” refers to applying pressure, and “electricity” conforms to accelerating electrons [3]. Piezoelectricity is a fascinating phenomenon that involves the generation of electric charges in certain materials when subjected to mechanical stress or vibrations. This unique property has garnered significant attention in recent years due to its potential applications in renewable energy and power generation. The process of capturing energy that would otherwise be lost is known as energy harvesting, or energy scavenging [4]. Some of this wasted energy is collected by energy harvesting equipment, which then transforms it into electricity and uses it for energy production. With careful design, energy-harvesting technologies have the potential to fully substitute batteries in certain applications [5,6]. In contrary, a study has also been done to harvest wave energy by using piezoelectric [7]. Here, two different shapes of piezoelectric harvester are compared by using COMSOL software. The Malaysian government has never stopped looking for and researching additional potential renewable energy sources in addition to the primary energy sources (such as natural gas, oil, coal, and hydropower). Renewable energy only accounts for 2.1% of global energy consumption, despite consumption growing quickly [8,9].

Based on research paper by Hanim M. Yatim *et al.,* on the development of piezoelectric model as an energy harvester from mechanical vibration, the possibility of using a piezoelectric converter to capture vibration as a source of usable power for applications. The problem in this research was to reuse wasted vibration energy from the environment rather than letting it dissipate [10]. Self-powered systems based on harvesting ambient energy become viable alternatives, eliminating the need for batteries and creating low-maintenance, autonomous systems. Several different ambient sources have already been exploited [11]. To achieve high-power generation, the frequency up-conversion method uses the impact between the inertial mass system and the piezo stack transducer system to enable the piezoelectric transducer to operate at the transient resonant frequency response despite the input vibration frequency being much lower than the transducer one [12].

The efficiency of rectifier plays a vital role in harvesting small energy. The author, K.S.Thanga Pandian *et al.,* studied the proposed rectifier solves the dc-offset problem of the comparator-based active diode, minimizes the voltage drop along the conduction path, and extracts more power from the transducer, all of which lead to better power extraction and conversion capability. The output voltage of a conventional full bridge rectifier is 0.85V, then the output voltage of proposed rectifier with compared based active diode is 1.15V and the output voltage of the proposed rectifier with op-amp based active diode is 1.18V. The rectifier was designed and fabricated in 0.18-μm CMOS technology to maximize extracted power [13]. Geffrey K. Ottman *et al.,* [14] in their paper entitled Adaptive Piezoelectric Energy Harvesting Circuit for Wireless Remote Power Supply, proposed an approach to harvest electrical energy from a mechanically excited piezoelectric element. The problem stated in this paper is to develop an approach that maximizes the power transferred from a vibrating piezoelectric transducer to an electrochemical battery. An ac–dc rectifier model is used to determine the point of optimal power flow for the piezoelectric element. Based on the study conducted, the higher the resistance, the higher the value of voltages. Meanwhile, the current decreases.

The research on Dynamics for Droplet-Based Electricity paper by Xiang Wang *et al.,* proposed a developed dynamic model of surface charge density that can explain the underlying mechanism for the droplet-based electricity generator, DEG [15]. The developed mechanism was 15 mm×2 mm piece of copper electrode lies on the top surface of a PTFE film with a dimension of 25 mm×55 mm×0.03 mm, whose back side was coated with gold electrode. The PTFE film was attached to a class slide for support. A technique is found to identify the efficiency of the impact mechanism where scavenging energy from raindrop impacts has the potential as a power 12 source for electronic devices and acts as an alternative method of generating electrical power [16]. It is observed that charging of supercapacitor with the converter circuit is advantageous compared to charging directly with a rectifier, when the harvester is excited with higher amplitude of vibration. The charging time for the supercapacitor is from 0 to 2.7 V, when connected with rectifier and with the multi-input buck–boost converter is measured to be 195 and 162 min, respectively, for the excitation voltage of 20 Vpp [17]. A light-emitting diode, or LED, is a low-energy light source. They are tiny, lack a filament, and do not get particularly hot. They are also easy enough to integrate into beginning electronics projects [18]. The lowest input voltage for LED was 1.7 volts for infrared LED meanwhile ultra-blue needs high input voltage which is 4V. To be able to light up the LED, electric current in the LED must be large enough. A DC – DC buck converter approach is deployed to amplify the current by reducing the voltage output [19].

One source of typical lost energy is the ambient vibrations present around most machines and biological systems. Based on the statement, Henry A. Sodano, and Daniel J. Inman [20] researched on Comparison of Piezoelectric Energy Harvesting Devices for Recharging Batteries. The objective is to determine each of their abilities to transform ambient vibration into electrical energy and their capability to recharge a discharged battery. The method was at 'random location' because no effort was made in optimizing the placement of the accelerometer to produce the maximum magnitude of vibration, nor is the compressor the optimal location in the engine compartment for obtaining vibration energy. For power storage it is better to use a rechargeable battery than a super capacitor as rechargeable batteries have high energy stored per unit weight and a slower discharge response [21].

Rainfall, an elemental force of nature, has long been admired for its life-giving properties. Yet, beneath its serene exterior lies a dynamic interplay of kinetic energy as raindrops descend upon various surfaces. The intriguing proposition of converting this kinetic energy into usable electrical power, made possible by piezoelectric materials, holds promise for addressing energy challenges in innovative ways. Piezoelectricity, the phenomenon of generating an electric charge in certain materials when subjected to mechanical stress, has already demonstrated its prowess in a range of applications, from electronic devices to energy harvesting. Extending its application to rainfall energy harvesting introduces a novel approach that capitalizes on the mechanical energy imparted by raindrops as they strike surfaces, such as rooftops, pavements, or specially designed structures.

This research is an initial study that extend the applications of the previous studies and aims to design piezoelectric energy harvesting with a variant array of piezoelectric connections and simulate the circuit using Proteus software before developing the system for rainfall energy generation. The optimal array configuration will undoubtedly lead to the potential applications of piezoelectric energy harvesting from rainfall, offering insights into a greener and more self-sufficient energy future.

2. Methodology

As shown in Figure 1, vibrational energy is converted to electrical energy by piezoelectric. The voltage formed is an AC voltage. The generated AC voltage is converted to DC voltage form using a rectifier with four diodes. As the voltage output from AC/DC is lower, the voltage is transmitted through a DC/DC circuit to enhance the value of DC voltage. The DC/DC boost converter is used as the voltage drop on each component and load is considered. The minimum 5V input voltage is experimented with to charge a 3.7V rechargeable battery and light up a 1.5V LED light. A variety of array connection topologies, including series, parallel, and combination series and parallel topologies, are examined during the harvesting step. The inquiry into the output is carried out by comparing the best output with various forms of connections for the piezoelectric array. Five and ten units of piezoelectric disc are employed and arranged in a certain array connection respectively. Piezoelectric power harvesting uses four different types of array connections: series, parallel, combination series and parallel, and combination parallel and series.

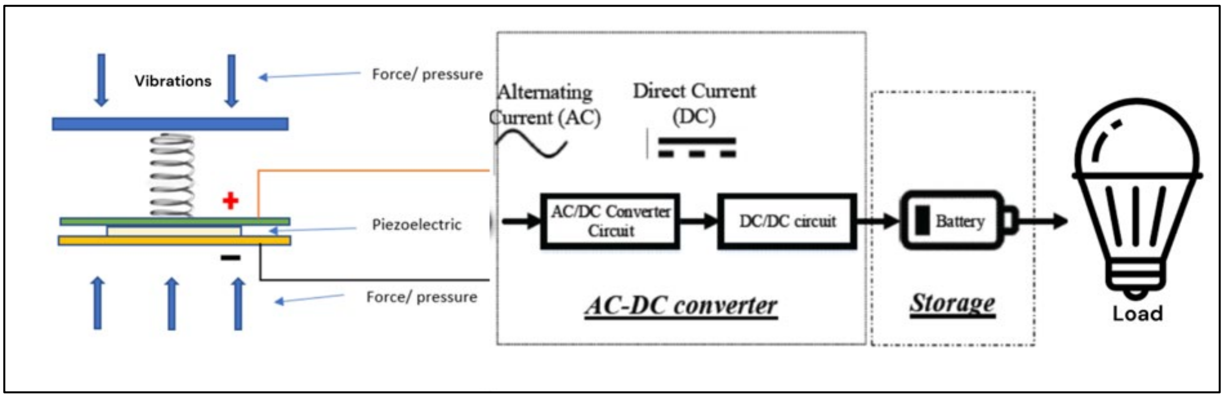

Fig. 1. Block diagram of piezoelectric energy harvesting device

Using the analogous circuit depicted in Figure 2, it is possible to calculate the electrical output of a piezoelectric device. This circuit's internal capacitance, C_p functions as a piezoelectric disc and serves as an AC current source. The current source's amplitude, p is influenced by the vibration's displacement and frequency. Eq. (1) and Eq. (2) together indicate the voltage where f_p is the frequency at which the piezoelectric harvester is activated.

$$v_s = v_p \sin \omega_p t \tag{1}$$

$$\omega_p = 2\pi f_p \tag{2}$$

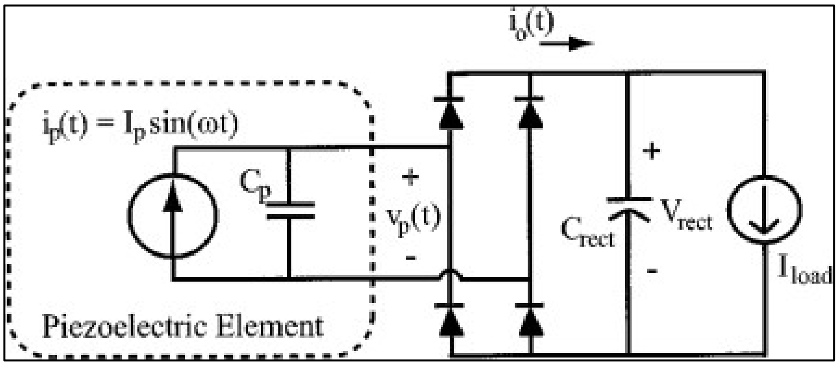

Fig. 2. Piezoelectric element model with ac-dc rectifier and load [4]

Next, the circuit model is then simulated using Proteus Software. The output power from the piezoelectric generator was produced as an AC source, which makes it impossible to use it directly for low-load electronic equipment. As a result, it needs to be converted into a DC source using an AC-DC converter circuit. The converting circuit must be able to maximize the power from the piezoelectric energy harvester.

Table 1 shows the parameter of piezoelectric used in the simulation. In this case, the working voltage for one piezoelectric has been defined to be 1.5V. The period has been defined as 20ms (milliseconds). This refers to the time it takes for the piezoelectric material to complete one cycle after the vibration occurred. In this case, the frequency has been defined as 50 Hz for the input vibrations. The amount of electrical resistance that the piezoelectric material is connected to might affect the electrical output of the material.

Table 1
Simulated parameter for one piezoelectric

Parameter	Value
Working Voltage	1.5V
Time Period	20ms
Frequency	50 Hz

In Proteus simulation, the components include the parameter of piezoelectric from Table 1 whilst Figure 3 depicts the modelling of the piezoelectric generator configuration connection. The piezoelectric generator simulated by connecting it in a parallel and series configuration using an array configuration that ranged from 5 units to 10 units.

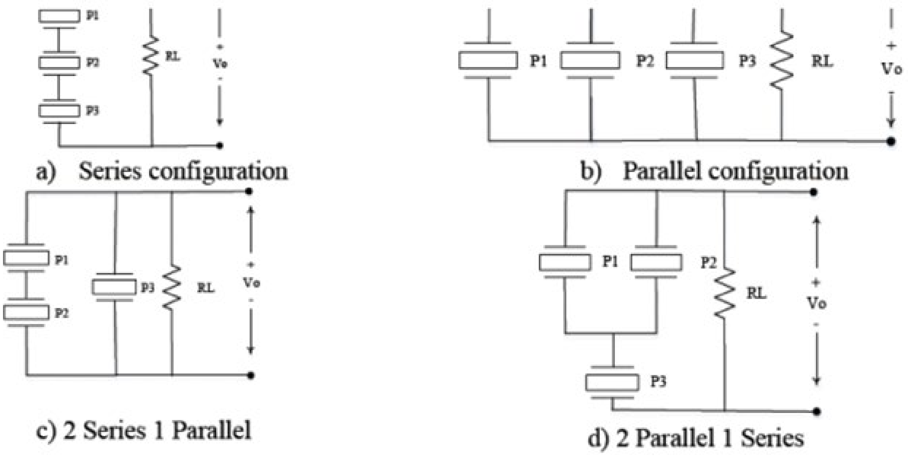

Fig. 3. Configuration circuit of piezoelectric generator connection [4]

In this simulation, the output and behaviour of the piezoelectric generator were obtained as the number of units increased incrementally by five with various types of circuit topologies. The array connections on simulating a group of piezoelectric discs are in each of the following four configurations: series (S), parallel (P), combination series-parallel (SP), and combination parallel-series (PS).

3. Results

3.1 Result for Parallel Piezoelectric Configurations

The results of parallel configuration of piezoelectric as shown in Figure 4 with five piezoelectric elements are observed. The output DC voltage obtained from the simulation was 4.2 Vdc as shown in Figure 5. This indicates that the piezoelectric array in parallel able to convert a portion of the applied mechanical energy into electrical energy, resulting in a DC voltage output. The graph obtained from the simulation showed that the output voltage increased slightly and then remained constant for a time domain of 20 ms.

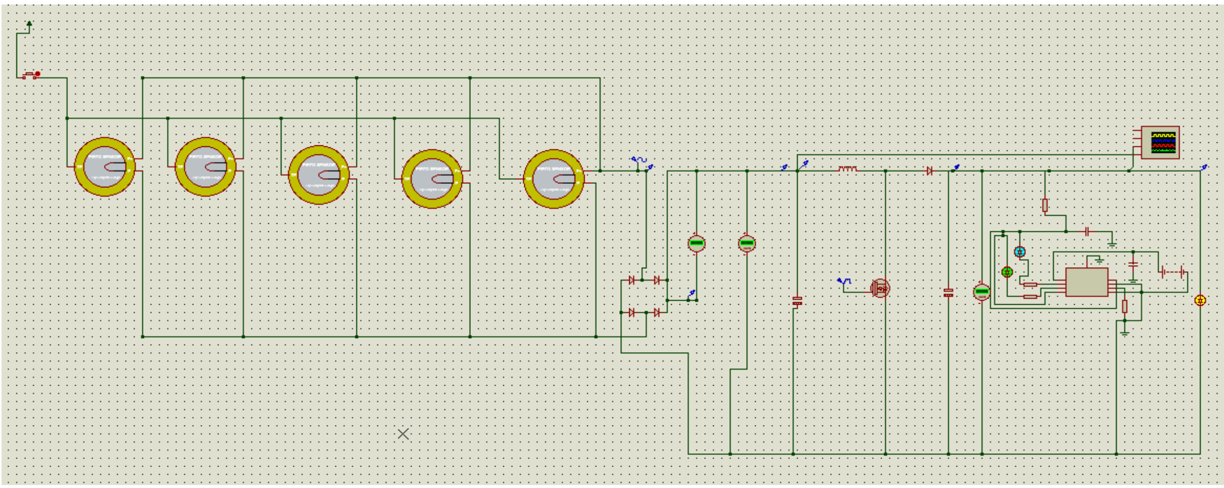

Fig. 4. The arrangement of piezoelectric array model for parallel connection circuit

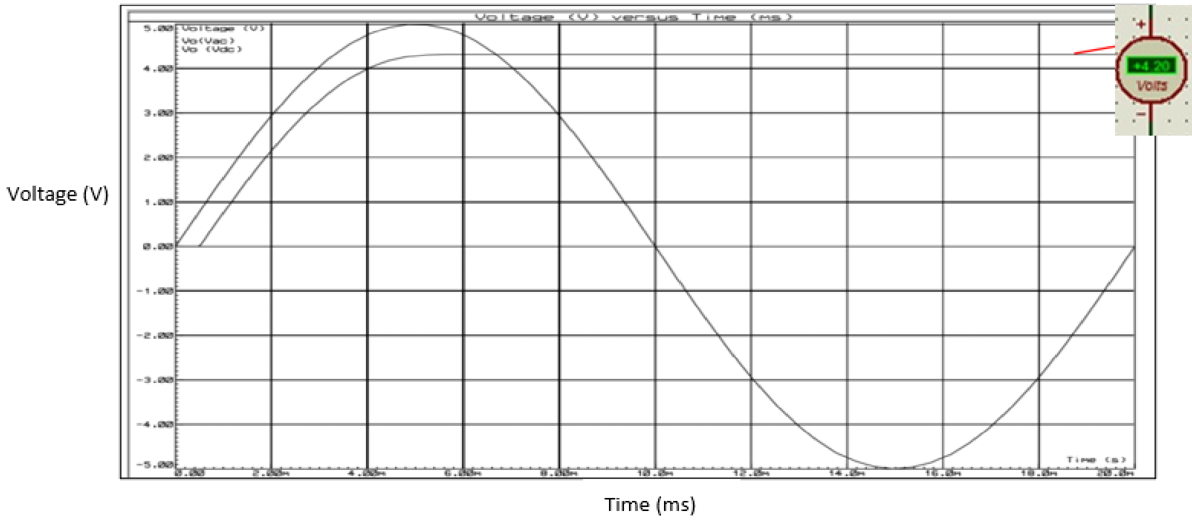

Fig. 5. The result of 5 units parallel connection

The frequency used in the simulation was 50 Hz, which act as constant input vibrations for AC power supply systems. The input voltage was also calculated as 3.54 Vrms, which represents the root mean square value of the AC voltage that would produce the same average power as the DC voltage obtained from the simulation. Figure 6 shows the results of additional five piezoelectric on the model. The results show the increased of piezoelectric disc resulting on increased of voltage output. The voltage obtained are 8.44 Vdc as close view shown in Figure 8. There were increment on the voltage input which is 10 Vac as the piezoelectric is added. Overall, the simulated parallel configuration of piezoelectric in this scenario was able to generate a steady DC voltage output from an AC source, demonstrating the potential for piezoelectric materials to be used as energy harvesters in various applications.

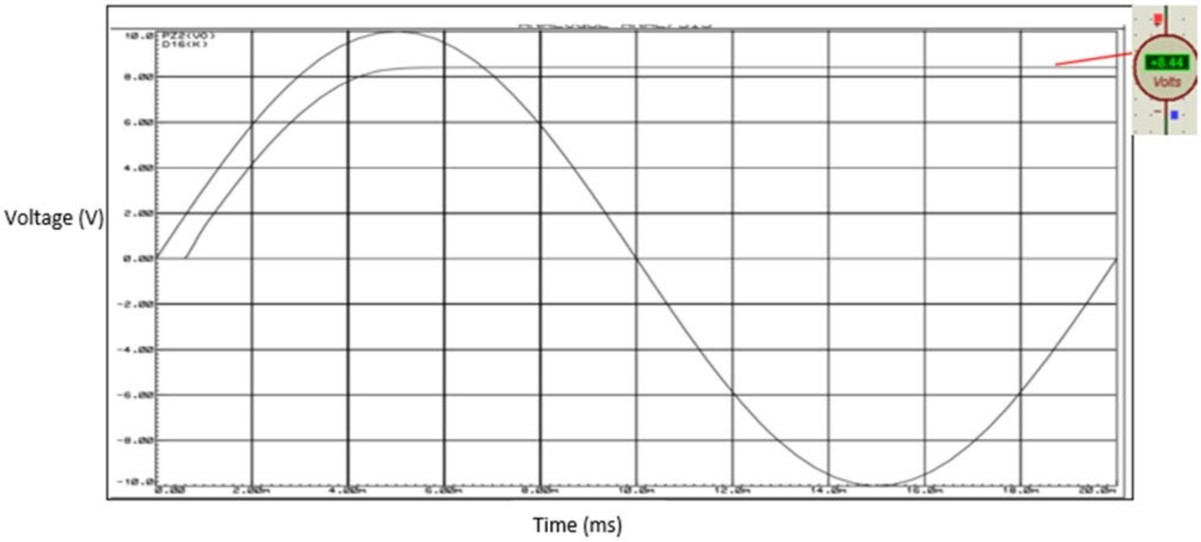

Fig. 6. The result of 10 units parallel connection

3.2 Result for Series Piezoelectric Configurations

For series configuration, the same working AC voltage and parameters was applied to the piezoelectric array model as shown in Figure 7.

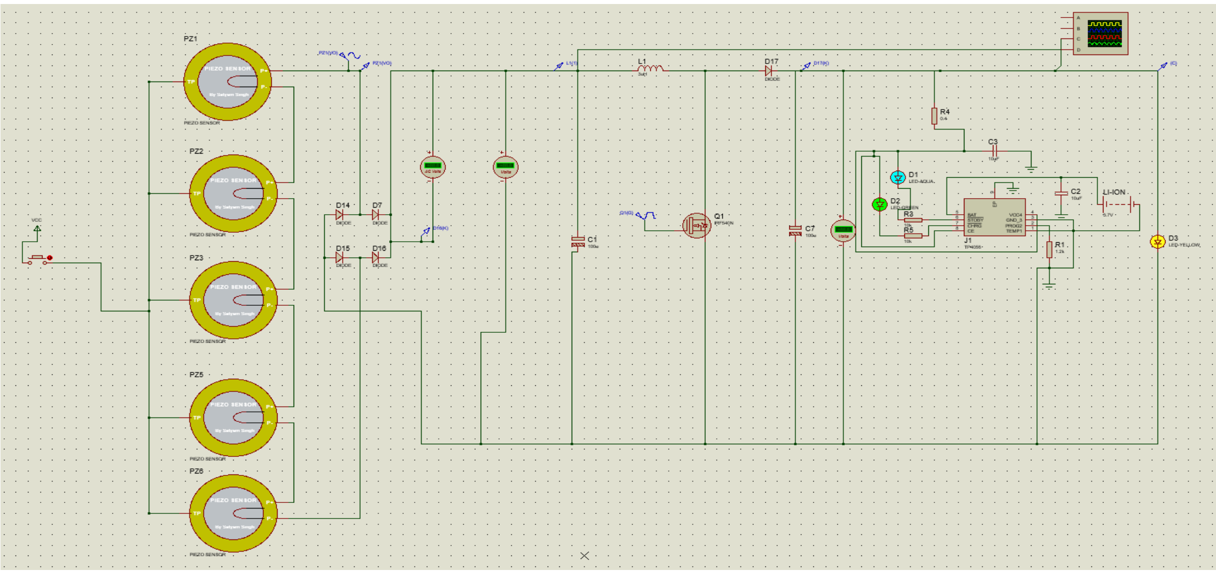

Fig. 7. The arrangement of piezoelectric array model for series connection circuit

As in Figure 8, the peak output DC voltage obtained from the simulation was 4.50 Vdc for 5 units of piezoelectric. This indicates that the piezoelectric array was able to convert a portion of the applied mechanical energy into electrical energy, resulting in a DC voltage output.

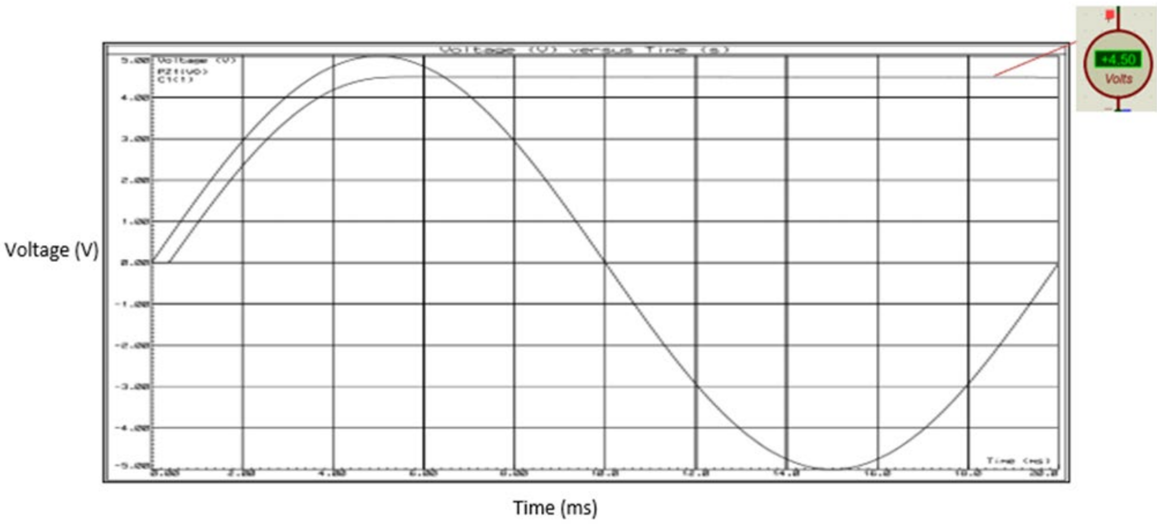

Fig. 8. The result of 5 units series connection

The graph obtained from the simulation showed in Figure 9 below indicates the output voltage for 10 units of piezoelectric which the values obtained are 8.54 Vdc and then remained constant for a time domain of 20ms. This indicates that the piezoelectric array was able to generate an increase of steady DC voltage output as the piezoelectric units is added. A load of LED with 1.5 Vdc lighten up and battery charging is applied in this simulation. Due to some voltage drop happened in this simulation, the input value is not the same as output voltage. Overall, compared to the parallel configuration, the series configuration was able to generate a higher output voltage but with a lower output current, making it suitable for applications that require higher voltages but lower currents.

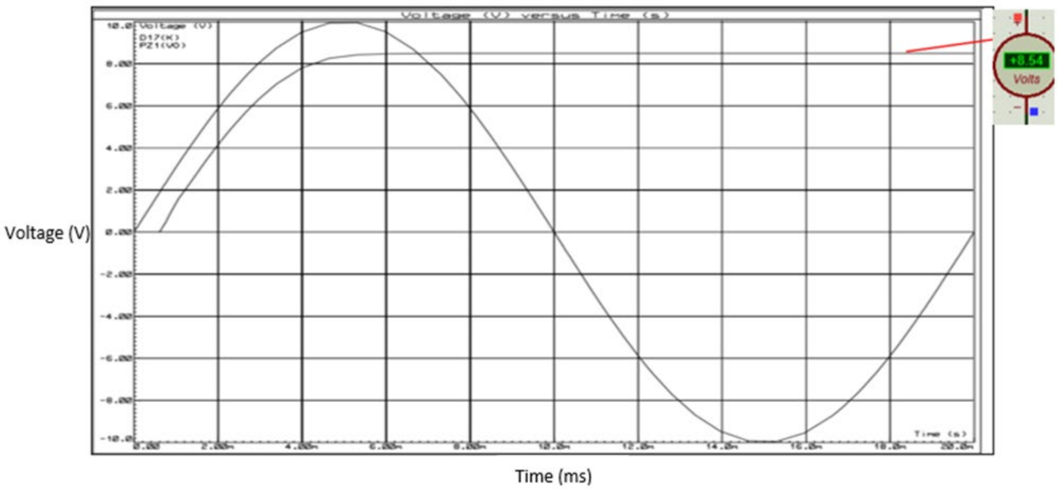

Fig. 9. The result of 10 units series connection

3.3 Result for Combination of Series-Parallel Piezoelectric Configurations

The configuration used in this case was 4 P 1 S, which means that 4 piezoelectric elements were connected in parallel and then connected in series with another set piezoelectric elements in parallel. Alternatively, 4 S 1 P configuration can be used, which means that 4 piezoelectric elements were connected in series and then connected in parallel with another set of piezoelectric elements in series. The output DC voltage obtained for both 4 P 1 S and 4 S 1 P was observed with different arrangement as shown in Figure 10 and Figure 11 below.

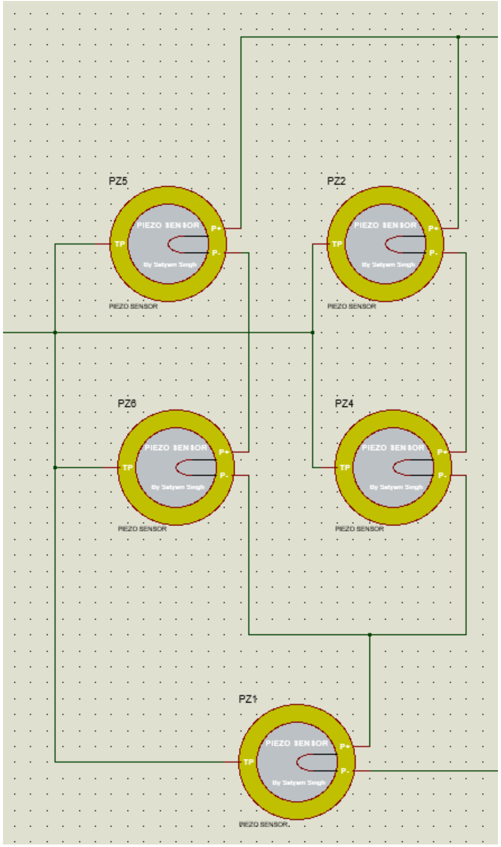

Fig. 10. The arrangement of 4 P 1 S configurations

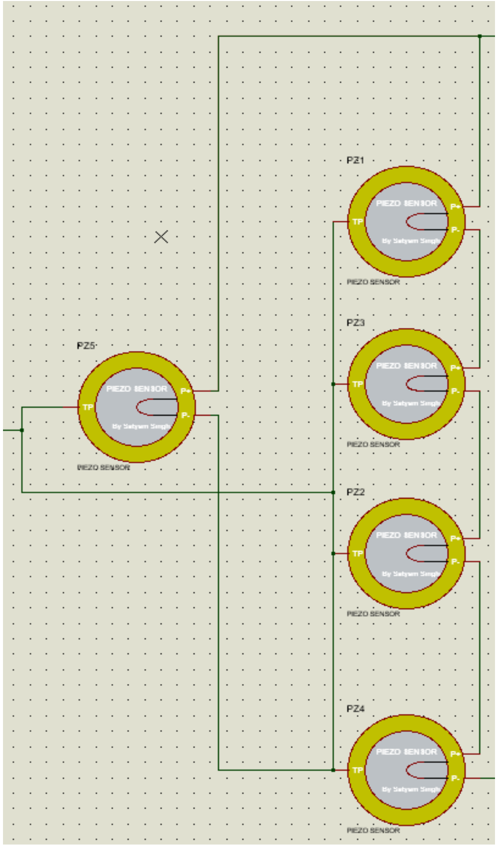

Fig. 11. The arrangement of 4 S 1 P configurations

Next, the maximum values obtained for both arrays are 4.44 Vdc as the graph obtained and illustrated in Figure 12. It shows a slight increase starting at 0.5ms until 5.0 ms and remain constant DC after that. Based on observation, when the push button is released, the voltage at 4 P 1 S recorded a longer time to decrease compared to 4 S 1 P. This indicates that every unit that is connected in a parallel circuit gets equal amount of voltage in each loop compared to series circuit which conserve the same voltage in only one loop.

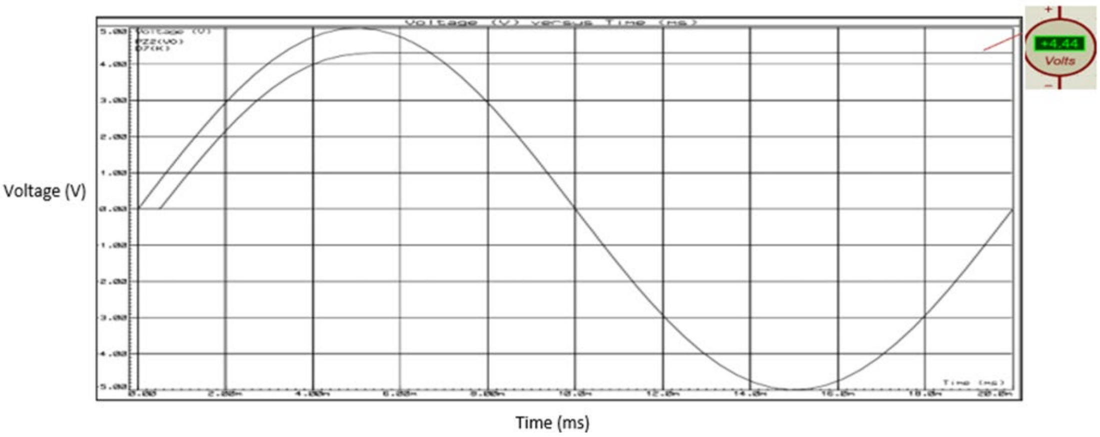

Fig. 12. Simulated result of series-parallel configurations

The series-parallel configuration allows for an increase in output voltage, which can be important in applications where a higher voltage is required. Thus, the advantage of the series-parallel configuration is it allows for flexibility in the design of the piezoelectric system, as different configurations can be used depending on the specific requirements of the application.

3.4 The Comparison of Various Types of Array Configurations

The simulation is performed by applying a mechanical stress to the piezoelectric array and measuring the output voltage across different types of arrays. The simulation results are then analysed to compare the output voltage of different array configurations as shown in Figure 13. The first configuration analysed is the series connection of piezoelectric elements followed by parallel and series-parallel connections. The increasing number of piezoelectric elements from 5 units to 10 units in the series-connected array increased the output voltage, resulted from 4.50 V to 8.54 V. The second configuration analysed is the parallel connection of piezoelectric elements. In this configuration, the simulation results show that the output voltage of the parallel-connected array increased from 4.2 V to 8.44 V as the piezoelectric units increased from 5 units to 10 units. The last array to observe was the combination of series-parallel configurations with 5 units of piezoelectric connections. The output voltage in series configurations is much higher compared to parallel and series-parallel configurations as the conservation of energy is applied from the property of Kirchhoff's law which stated algebraic sum of every voltage in the loop must be equal to zero.

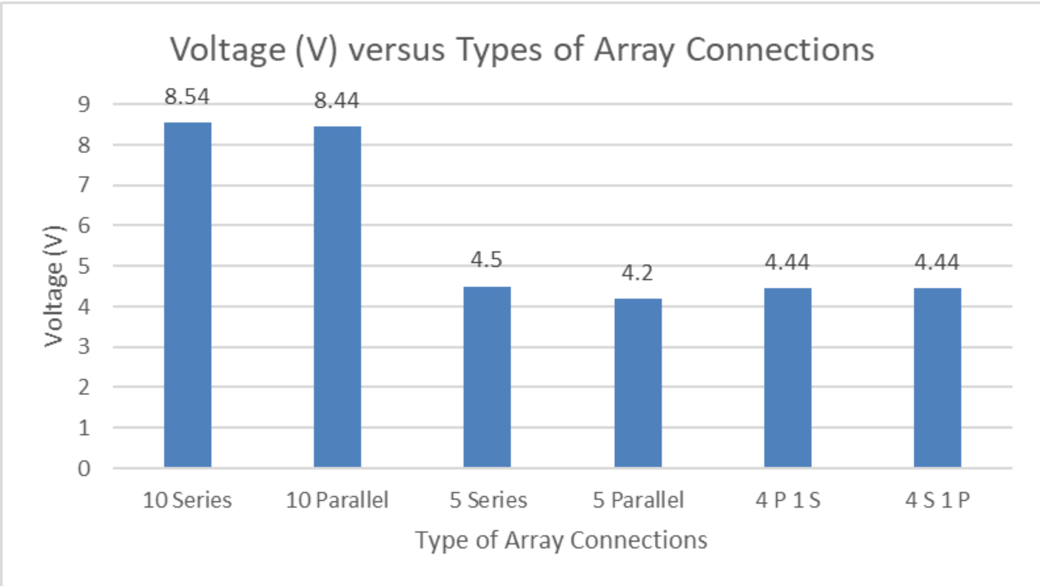

Fig. 13. Number of discs versus voltage output in variant types of array configuration

4. Conclusions

In conclusion, the research on simulation of energy harvesting using piezoelectric has successfully achieved its objectives. The study focused on investigating the best array connections from variant arrays of piezoelectric connections by identifying and simulating a system with battery charging using piezoelectric-based technology. The use of piezoelectric materials offers a promising alternative to traditional methods of energy generation. The result obtained shows that the series configuration gave the highest output voltage of all, and it is possible to increase the voltage by keep increasing the number of piezoelectric used. The development of a simulation model using piezoelectric-based systems demonstrated the feasibility of using this technology to generate electricity. This will undoubtedly lead to the potential applications of piezoelectric energy harvesting from rainfall, offering insights into a greener and more self-sufficient energy future. For future study, these results will be taken as a countable measure for developing the hardware prototype system for harvesting electrical energy from rainfall.

Acknowledgement
This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q386).

References

[1] Arndt, Channing, Faaiqa Hartley, Gregory Ireland, Kristi Mahrt, Bruno Merven, and Jarrad Wright. "Developments in variable renewable energy and implications for developing countries." *Current Sustainable/Renewable Energy Reports* 5 (2018): 240-246. https://doi.org/10.1007/s40518-018-0121-9

[2] Kroposki, Benjamin. "Integrating high levels of variable renewable energy into electric power systems." *Journal of Modern Power Systems and Clean Energy* 5, no. 6 (2017): 831-837. https://doi.org/10.1007/s40565-017-0339-3

[3] Liang, Zhang, Chang-Feng Yan, Sami Rtimi, and Jayasundera Bandara. "Piezoelectric materials for catalytic/photocatalytic removal of pollutants: Recent advances and outlook." *Applied Catalysis B: Environmental* 241 (2019): 256-269. https://doi.org/10.1016/j.apcatb.2018.09.028

[4] Chetto, Maryline, and Audrey Queudet. *Energy autonomy of real-time systems*. Elsevier, 2016. https://doi.org/10.1016/B978-1-78548-125-3.50003-8

[5] Adina, P., P. Petrica, T. Latinovic, and C. Barz. "Research about harvesting energy devices and storage method." *Carpathian Journal of Electrical Engineering* 4, no. 2 (2015): 102-120.

[6] Wang, Qi, Chong Shen, Kun Zhang, and Liqiang Zheng. "Super-capacitor and Li-polymer battery hybrid energy storage for kinetic energy harvesting applications." In *2017 IEEE Conference on Energy Conversion (CENCON)*, pp. 73-77. IEEE, 2017. https://doi.org/10.1109/CENCON.2017.8262461

[7] Fang, Liew Hui, Rosemizi Abd Rahim, Muhammad Izuan Fahmi, and Vmalen Kupusamy. "Modelling and Characterization Piezoelectric Transducer for Sound Wave Energy Harvesting." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 102, no. 2 (2023): 81-98. https://doi.org/10.37934/arfmts.102.2.8198

[8] Williams, Alexander J., Matheus F. Torquato, Ian M. Cameron, Ashraf A. Fahmy, and Johann Sienz. "Survey of energy harvesting technologies for wireless sensor networks." *IEEE Access* 9 (2021): 77493-77510. http://dx.doi.org/10.1109/ACCESS.2021.3083697

[9] Ashnani, Mohammad Hossein Mohammadi, Anwar Johari, Haslenda Hashim, and Elham Hasani. "A source of renewable energy in Malaysia, why biodiesel?." *Renewable and Sustainable Energy Reviews* 35 (2014): 244-257. https://doi.org/10.1016/j.rser.2014.04.001

[10] Yatim, Hanim M., Fauzi M. Ismail, Shahrul E. Kosnan, Zulhaimi Mohammad, Fatihhi S. Januddi, and Adnan Bakri. "A development of piezoelectric model as an energy harvester from mechanical vibration." *Chemical Engineering Transactions* 63 (2018): 775-780. https://doi.org/10.3303/CET1863130

[11] Mishu, Mahmuda Khatun, Md Rokonuzzaman, Jagadeesh Pasupuleti, Mohammad Shakeri, Kazi Sajedur Rahman, Fazrena Azlee Hamid, Sieh Kiong Tiong, and Nowshad Amin. "Prospective efficient ambient energy harvesting sources for iot-equipped sensor applications." *Electronics* 9, no. 9 (2020): 1345. https://doi.org/10.3390/electronics9091345

[12] Shan, Guansong, and Meiling Zhu. "A piezo stack energy harvester with frequency up-conversion for rail track vibration." *Mechanical Systems and Signal Processing* 178 (2022): 109268. https://doi.org/10.1016/j.ymssp.2022.109268

[13] Thanga Pandian, Lenin Raja M.E. “High Efficiency Rectifier With Transducer In Piezoelectric Energy Harvesting Systems”, *International Journal of Advanced Information Science and Technology (IJAIST)* 34*,* no.34 (2015)

[14] Ottman, Geffrey K., Heath F. Hofmann, Archin C. Bhatt, and George A. Lesieutre. "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply." *IEEE Transactions on power electronics* 17, no. 5 (2002): 669-676. https://doi.org/10.1109/TPEL.2002.802194

[15] Wang, Xiang, Sunmiao Fang, Jin Tan, Tao Hu, Weicun Chu, Jun Yin, Jianxin Zhou, and Wanlin Guo. "Dynamics for droplet-based electricity generators." *Nano Energy* 80 (2021): 105558. https://doi.org/10.1016/j.nanoen.2020.105558

[16] Ilyas, Mohammad Adnan, and Jonathan Swingler. "Towards a prototype module for piezoelectric energy harvesting from raindrop impacts." *Energy* 125 (2017): 716-725. https://doi.org/10.1016/j.energy.2017.02.071

[17] Abidin, Nik Ahmad Kamil Zainal, Norkharziana Mohd Nayan, Azuwa Ali, N. A. Azli, and N. M. Nordin. "Analysis of AC-DC converter circuit performance with difference piezoelectric transducer array connection." *International*

Journal of Integrated Engineering 12, no. 7 (2020): 20-27. https://doi.org/10.1088/1742-6596%2F1432%2F1%2F012042

[18] Raghavendran, Srinivasan, Mangalanathan Umapathy, and Lakshmi Ravikularaman Karlmarx. "Supercapacitor charging from piezoelectric energy harvesters using multi-input buck–boost converter." *IET Circuits, Devices & Systems* 12, no. 6 (2018): 746-752. https://doi.org/10.1049/iet-cds.2018.5069

[19] Dayou, Jedol, and Man Sang Chow. "Performance study of piezoelectric energy harvesting to flash a LED." *International Journal of Renewable Energy Research* 1, no. 4 (2011): 323-332.

[20] Sodano, Henry A., Daniel J. Inman, and Gyuhae Park. "Comparison of piezoelectric energy harvesting devices for recharging batteries." *Journal of intelligent material systems and structures* 16, no. 10 (2005): 799-807. https://doi.org/10.1177/1045389X05056681

[21] Livingston, J. John, and Mahalingam Hemalatha. "Charging an electronic gadget using piezoelectricity." *Indian Journal of Science and Technology* 7, no. 7 (2014): 945-948. http://dx.doi.org/10.9790/1676-1202024649