Study of the configuration of multi-source energy harvesting systems based on piezoelectric nanogenerator as a clean energy harvester

Saparullah, N Mufti, P Adinegoro, H Wisodo

Department of Physics, Faculty of Mathematics and Natural Sciences, State University of Malang, Jl. Semarang 5, Malang 65145, Indonesia

E-mail: nandang.mufti.fmipa@um.ac.id

Abstract. This paper presents the connection configuration of a multi-source piezoelectric transducer to extract energy from ambient mechanical forces to power up electronic devices. The configurations are optimized by applying a full-bridge rectifier (FBR) as an interface circuit to complete alternating to direct current (AC-DC) transformation before powering up any electronic devices. The FBR is varied in Silicon (Si-FBR) and Schottky (So-FBR) diodes to compare which one is more efficient. Six pieces of 35 mm piezoelectric transducer, PT, are connected in parallel and series connection then pressed under 20 N periodic force. The study shows that the configuration types of the multi-source PT have different results in harvesting mechanical energy. Experimental results show the maximum power can be harvested from six PTs in series for one and six Si-FBRs are 440 and 500 µW, respectively and for So-FBR obtained 150 and 730 µW. In a parallel configuration, maximum power can be harvested from six PTs for one and six Si-FBRs are 440 and 1050 µW, respectively and for So-FBR obtained 780 and 902 µW.

1. Introduction

Energy harvesting is a mechanism to utilize the abundant energy in the environment, convert it into a desirable form, and store it for future usage [1]. Energy harvesting has become desirable to study due to its capability to drive low-power devices such as wireless sensor networks, micro-system applications, and micro-devices [2–7]. Energy harvesting has become necessary research in various industries due to environmental pollution, energy shortage, chemical waste, and other issues [8–10]. Energy harvesters harvest energy from environments such as heat, mechanical vibrations, and electromagnetic radiation [11–13]. Using alternative ways in powering devices as the primary source will actualize green energy and fulfill the power demand and also can reduce the cost of electronic maintenance, pollution from conventional energy sources, and chemical waste from batteries [8], [14–16].

One of the most popular devices used in harvesting mechanical vibration is a piezoelectric transducer [17]. The piezoelectric transducer produces electrical charge due to physical deform, or conversely, experiences mechanical deformation in the presence of electric field [18,19]. However, a piezoelectric transducer generates alternating current (AC), while in electronic devices commonly driven by DC, it requires a rectifier bridge to perform AC to DC transformation [2,4]. Full-bridge rectifiers (FBR) are commonly used as interface circuits due to their simplicity, stability, low cost, and reliability [4,20]. FBR is a common part of many applications, consisting of four diodes [21,22] and arranged in a
A single-source piezoelectric energy harvester can produce power in μW [6]. However, it is insufficient to drive any electronic devices, so it needs to be enhanced. Some methods have been proposed to enhance the power extraction from a piezoelectric by applying interface circuit such as synchronized switch harvesting on an inductor (SSHII) [3,4,10] and on a capacitor (SSHC) [23–25]. Unfortunately, single-source piezoelectric has limitations in power output and is still insufficient to drive electronic devices. The single-source has to be improved to become a multi-source piezoelectric energy harvester to enhance the total power extraction. Multi-source piezoelectric extracts power from the environment, applying several connected piezoelectric transducers into a single output [9,15], [26–31]. A multi-source piezoelectric energy harvester requires an appropriate configuration to optimize the power extraction performance of the harvester. In this work, we study the proper configuration of the multi-source piezoelectric energy harvester, which can be conducted in power extracting to enhance the order of the power extraction from the environment.

2. Method
The method used in this research was the simple bending method [32]. Six pieces of piezoelectric transducer (PT) with a diameter of 35 mm, were prepared in an array of 2 x 3 and placed between two 8 x 12 cm² of acrylic planes, as shown in Figure 2. The FBR was built using four silicon diodes (1N4007) and four Schottky diodes (KL4). The electrodes of the PTs were connected in series and parallel configuration, and every single configuration was given one and six FBRs (each single PT is given an FBR). A 20 N force was applied to the array, and then the open-circuit voltage and the short circuit current were measured using Keithley 6517B.
The force was generated from a custom force generator device built from 12 volts geared DC motor ZGY370. The motor was connected to a vertical leg which consisted of three ball-joint sticks. The leg moved up and down depending on the rotation of the motor. The end of the leg was connected with a spring to avoid the motor stops moving when the leg and the surface of the array collide.

3. Results and Discussion
Six PTs (Ø 35 mm) are arranged in series and parallel configurations. The FBRs are built from p-n silicon diode and Schottky diode as an interface circuit to rectify the AC into DC, from the piezoelectric.

Figure 2. Six pieces of PT were placed in array 2 x 3 and connected in \( n = 6 \) pieces. (a) top view, (b) cross-section view, (c) series configuration with one FBR, (d) parallel configuration with one FBR, (e) series configuration with FBR for each PT, and (f) parallel configuration with FBR for each PT.
The performance of the six PTs in series and parallel configuration is measured using Keithley 6517B with one and six FBRs as interface circuits. The maximum power, $P_{\text{max}}$, is obtained from equation (1).

$$P_{\text{max}} = V_{\text{oc}} \times I_{\text{sc}}$$  \hspace{1cm} (1)

The maximum value of $V_{\text{oc}}$ and $I_{\text{sc}}$ are presented in figure 3. The maximum $V_{\text{oc}}$ and the $I_{\text{sc}}$ in the series configuration, as seen in figure 3a, for one and six silicon FBRs are 202.18 volts, 2.18 $\mu$A, and 77.95 volts, 6.42 $\mu$A respectively, so that the $P_{\text{max}}$ obtained is 440 $\mu$W and 500 $\mu$W. The performance in parallel configuration shows different results compared to the series configuration. As seen in Figure 3b, the maximum $V_{\text{oc}}$ and $I_{\text{sc}}$ for one and six silicon FBRs in the parallel configuration are 22.8 volts, 19.2 $\mu$A, and 49.8 volts, 21 $\mu$A, respectively. Hence, the $P_{\text{max}}$ obtained for one and six silicon FBRs in parallel configuration is 440 and 1050 $\mu$W. As illustrated in figure 3, the $V_{\text{oc}}$ in series configuration (both one and six silicon FBRs) are higher compared to the parallel configuration, but the $I_{\text{sc}}$ and the $P_{\text{max}}$ obtained are lower.

Similar behavior is shown when using Schottky FBR. The maximum $V_{\text{oc}}$ and $I_{\text{sc}}$ using one and six Schottky FBRs in the series configuration are 46.76 volts, 3.2 $\mu$A and 95.67 volts, 7.64 $\mu$A, respectively. Thus, the maximum power for one and six Schottky FBRs are 150 and 730 $\mu$W, respectively. In the parallel configuration, the $V_{\text{oc}}$ and $I_{\text{sc}}$ for one and six Schottky FBRs are 36.49 volts, 21.3 $\mu$A, and 35.74 volts, 25.25 $\mu$A, hence the maximum powers obtained are 780 and 902 $\mu$W, respectively. The results are shown in figure 3, and figure 4 strengthen that the parallel configuration is more efficient than the series configuration. Also, applying an FBR for each PT (six FBRs for six PTs arrangement) is more efficient than applying only one FBR for any configuration.
Therefore, the total amount of \( V_{oc} \) in series configuration is equal to the sum of the \( V_p \), which is resulted from every single PT. In an ideal condition, the total amount of \( V_{OC} \) reached from \( n \) pieces of
the PT in series configuration is equal to $V_{oc} = nV_p$ and the total resistance $R = nR_p$. Thus, the $I_{SC}$ is equal to $V_{oc}/R$.

\[ \sum I_{out} = \sum I_{in} \quad (4) \]

In parallel configuration (figure 5b), we see the PT as a current source so that the total amount of the $I_{SC}$ is equal to the sum of the $I_p$ as Kirchhoff’s law says all the currents entering and leaving must be equal [18]. In an ideal condition, the total amount of the $I_{sc}$ can be reached from $n$ pieces of the PT in parallel configuration is equal to $I_{sc} = nI_p$ and the total amount of the resistance $R = R_p/n$. Thus, the $V_{oc}$ is equal to $I_{sc}R$ [19].

However, the ideal condition is almost impossible to reach. Differences between the signals can arise due to small differences between the PTs. As seen in equations (5) and (6) representing the AC signals of the two PTs, a phase angle, $\phi$, a difference of frequency, $\Delta f$, and a difference in amplitude, $\Delta A$, could appear. These differences highly depend on the method of excitation. Differences in frequency and phase mostly occur in the fluid flow excitation and the difference in amplitude mostly occurs in mechanical vibrations. However, amplitude differences would be a major concern due to the difficulty in manufacturing multi-source PTs with the same natural frequency [30].

\[ V_{p1} = A_{p1} \sin (f_{p1} \ast t) \quad (5) \]
\[ V_{p1} = A_{p2} \sin (f_{p2} \ast t + \phi) \quad (6) \]

The differences in phase, frequency, or amplitude conduce inconsistent output values of the PT configurations. This case becomes worse while the multiple PTs are connected directly without FBR due to the output value of a single PT in the configurations may be positive or negative at a certain time. For example, if the output values of some PTs are positive and the others are negative, instead of the total output value as a summation, it becomes a subtraction. However, reducing the $\phi$ and the $\Delta f$ in this study has been conducted by placing the PTs in the acrylic sandwich, so the applied force will be done in a similar phase and period due to the stiffness of the acrylic planes. In the other hand reducing the $\Delta A$ by applying FBR for each PT before connecting them in series and parallel configuration. As seen in Table 1, the performances of the configurations show a significant increment after applying FBR for each PT (6 FBR).

Ideally, the power extraction in both series and parallel configuration has an identical value equal to the sum of the power of each PT (as long as the force acting on each PT is similar). As seen in table 1, for six FBRs, the parallel shows a significant difference compared to the series configuration in which the parallel has a higher value. For six silicon FBRs, $P_{max}$ parallel configuration is 2.1 times larger.
compared to the series configuration and 1.24 times larger for six Schottky FBRs. The difference in $P_{\text{max}}$ between both configurations is caused by power loss. Power loss can occur in the wiring connection and has a higher percentage to occur in series configuration compared to the parallel configuration [33]. Moreover, power loss also occurs in the diodes due to its characteristic of voltage drop (0.6-0.7 volts for silicon and 0.3-0.5 volts for Schottky) but has an insignificant impact in the case of high voltage signal (voltage drop $\ll$ voltage signal) [33].

Table 1. The output of the PT in the series and parallel configuration.

| Configuration | Diode  | Number of FBR | $V_{\text{OC}}$ (Volt) | $I_{\text{SC}}$ ($\mu$A) | $P$ ($\mu$W) |
|---------------|--------|---------------|------------------------|-------------------------|-------------|
| Series        | Silicon| 1             | 202.18                 | 2.18                    | 440         |
|               |        | 6             | 77.95                  | 6.42                    | 500         |
|               | Schottky| 1             | 46.76                  | 3.2                     | 150         |
|               |        | 6             | 95.67                  | 7.64                    | 730         |
| Parallel      | Silicon| 1             | 22.8                   | 19.2                    | 440         |
|               |        | 6             | 49.8                   | 21.3                    | 1050        |
|               | Schottky| 1             | 36.49                  | 25.25                   | 902         |

4. Conclusion
The work aims to study the appropriate configuration in multi-source piezoelectric energy harvesting. The results show the parallel configuration is more appropriate compared to the series configuration. It is because the power loss issue in the series configuration is larger compared to the parallel configuration. The maximum powers, $P_{\text{max}}$, for six silicon and Schottky FBRs in a parallel configuration, respectively, are 2.1 and 1.24 times larger compared to the series configuration. However, the diode provides an insignificant impact on power loss for high voltage signals while becoming a big issue in the case of the low voltage signals. Moreover, applying an FBR for each PT before connecting it in both configurations is more efficient in harvesting energy due to the difference in amplitude, $\Delta A$, for each PT at a certain time during the harvesting process can be reduced.

Acknowledgments
Financial support from PNBP LP2M Universitas Negeri Malang (18.3.39 /UN32.14.1/LT/2021) is acknowledged.

References
[1] Yadav J, Yadav D, Vashistha R, Goyal D P and Chhabra D 2019 Green energy generation through PEHF – a blueprint of alternate energy harvesting *Int. J. Green Energy* 16 242–255
[2] Chen Z, He J, Liu J and Xiong Y 2018 Switching Delay in Self-Powered Nonlinear Piezoelectric Vibration Energy Harvesting Circuit: Mechanisms, Effects, and Solution *IEEE Trans. Power Electron.* 34 2427–2440
[3] Liang J, Zhao Y and Zhao K 2018 Synchronized Triple Bias-Flip Interface Circuit for Piezoelectric Energy Harvesting Enhancement *IEEE Trans. Power Electron.* 34 275–286
[4] Du S and Seshia A A 2017 An Inductorless Bias-Flip Rectifier for Piezoelectric Energy Harvesting *IEEE J. Solid-State Circuits* 52 2746–2757
[5] Kong N and Ha D 2011 Low-Power Design of a Self-powered Piezoelectric Energy Harvesting System With Maximum Power Point Tracking *IEEE Trans. Power Electron.* 27 2298–2308
[6] Shim M, Kim J, Jeong J, Park S and Kim C 2015 Self-Powered 30 $\mu$W to 10 mW Piezoelectric Energy Harvesting System With 9.09 ms/V Maximum Power Point Tracking Time *IEEE J. Solid-State Circuits* 50 2367–2379
[7] Sorayani Bafqi M S, Bagherzadeh R and Latifi M 2015 Fabrication of composite PVDF-ZnO nanofiber mats by electrospinning for energy scavenging application with enhanced efficiency J. Polym. Res. 22 130

[8] Wang C, Wang S, Li Q J, Wang X, Gao Z and Zhang L 2018 Fabrication and performance of a power generation device based on stacked piezoelectric energy-harvesting units for pavements Energy Convers. Manag. 163 196–207

[9] Bai Y, Jantunen H and Juuti J 2018 Energy Harvesting Research: The Road from Single Source to Multisource Adv. Mater. 30 1707271

[10] Wu L, Do X D, Lee S G and Ha D S 2017 A Self-Powered and Optimal SSHI Circuit Integrated With an Active Rectifier for Piezoelectric Energy Harvesting IEEE Trans. Circuits Syst. Regul. Pap. 64 537–549

[11] Ko E J, et al. 2019 Synthesis and characterization of nanofiber-type hydrophobic organic materials as electrodes for improved performance of PVDF-based piezoelectric nanogenerators Nano Energy 58 1–22

[12] Khalifa M, Mahendran A and Anandhan S 2019 Durable, efficient, and flexible piezoelectric nanogenerator from electrospun PANI/HNT/PVDF blend nanocomposite Polym. Compos. 40 1663–1675

[13] Singh H H and Khare N 2018 Flexible ZnO-PVDF/PTFE based piezo-tribo hybrid nanogenerator Nano Energy 51 216–222

[14] Thakur P, et al. 2017 Superior performances of in situ synthesized ZnO/PVDF thin film based self-poled piezoelectric nanogenerator and self-charged photo-power bank with high durability Nano Energy 44 456–467

[15] Green C, Erturun U, Burnette M and Mossi K 2011 Modeling of Low Frequency Multi-Source Energy Harvesting Systems ASME 2011 Conference on Smart Materials, Adaptive Structures and Intelligent Systems 1 59–69

[16] Xia H and Chen R 2014 Design and analysis of a scalable harvesting interface for multi-source piezoelectric energy harvesting Sens. Actuators Phys. 218 33–40

[17] Chamanian S, Ulusan H, Koyuncuoglu A, Muhtaroglu A and Kulah H 2018 An Adaptable Interface Circuit With Multistage Energy Extraction for Low-Power Piezoelectric Energy Harvesting MEMS IEEE Trans. Power Electron. 34 2739–2747

[18] Erturk A and Inman D J 2011 Piezoelectric energy harvesting (Chichester: Wiley)

[19] Leprince-Wang Y 2015 Piezoelectric ZnO nanostructure for energy harvesting (NJ: ISTE Ltd; John Wiley & Sons, Inc)

[20] Umesh S, Venkatesha L and Usha A 2014 Active power factor correction technique for single phase full bridge rectifier 2014 International Conference on Advances in Energy Conversion Technologies (ICAECT) pp 130–135

[21] Fu M, Tang Z and Ma C 2018 Analysis and Optimized Design of Compensation Capacitors for a Megahertz WPT System Using Full-Bridge Rectifier IEEE Trans. Ind. Inform. 15 95–104

[22] Lv D, Zhang J and Dai Y 2015 Study on time and frequency-domain harmonic models of single-phase full bridge rectifiers 2015 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER) pp 1186–1191

[23] Du S, Jia Y, Zhao C, Amaratunga G A J and Seshia A A 2019 A Fully Integrated Split-Electrode SSHC Rectifier for Piezoelectric Energy Harvesting IEEE J. Solid-State Circuits 54 1733–1743

[24] Yue X and Du S 2021 Voltage Flip Efficiency Optimization of SSHC Rectifiers for Piezoelectric Energy Harvesting 2021 IEEE International Symposium on Circuits and Systems (ISCAS) pp 1–5

[25] Liu Y, Liu J, Wu Q, Yu H, Yiming H and Zhou Z 2020 SSHC: A Secure and Scalable Hybrid Consensus Protocol for Sharding Blockchains with a Formal Security Framework IEEE Trans. Dependable Secure Comput. pp 1–1
[26] Park H-M, Kwon J-S, Kim B-S and Kim D-S 2019 Multi-Source Based Energy Harvesting Architecture for IoT and Wearable System J. Korea Inst. Electron. Commun. Sci. 14 225–234
[27] Romani A, Paganelli R P and Tartagni M 2010 A scalable micro-power converter for multi-source piezoelectric energy harvesting applications Procedia Eng. 5 782–785
[28] Alghisi D, Ferrari M and Ferrari V 2014 Trigger Circuits in Battery-less Multi-source Power Management Electronics for Piezoelectric Energy Harvesters Procedia Eng. 87 1286–1289
[29] Choi M, Farinholt K M, Anton S, Lee J-R and Park G 2013 Multi-source energy harvesting for wireless SHM systems Proceedings Industrial and Comemrical Applicationts of Smart Structures Technologies p 869008
[30] Schlichting A, Tiwari R and Garcia E 2012 Passive multi-source energy harvesting schemes J. Intell. Mater. Syst. Struct. 23 1921–1935
[31] Schlichting A D, Tiwari R and Garcia E 2011 Multi-source energy harvester power management Proceedings Active and Passive Smart Structure and Integrated Systems p 79770J
[32] Carter R and Kensley R Introduction to piezoelectric transducers Piezo.com
[33] Zhao X, Shang Z, Luo G and Deng L 2015 A vibration energy harvester using AlN piezoelectric cantilever array Microelectron. Eng. 142 47–51