processes

Article

An Energy Storage Unit Design for a Piezoelectric Wind Energy Harvester with a High Total Harmonic Distortion

Davut Özhan [1,*] and Erol Kurt [2]

[1] Department of Electronics, Mardin Vocational High School, Mardin Artuklu University, Mardin TR-47100, Turkey
[2] Department of Electrical and Electronics Engineering, Technology Faculty, Gazi University, Ankara TR-06500, Turkey; ekurt@gazi.edu.tr
* Correspondence: davutozhan@artuklu.edu.tr

Abstract

A new energy storage unit, which is fed by a piezoelectric wind energy harvester, is explored. The outputs of a three-phase piezoelectric wind energy device have been initially recorded from the laboratory experiments. Following the records of voltage outputs, the power ranges of the device were measured at several hundred microwatts. The main issue of piezoelectric voltage generation is that voltage waveforms of piezoelectric materials have high total harmonic distortion (THD) with incredibly high subharmonics and superharmonics. Therefore, such a material reply causes a certain power loss at the output of the wind energy generator. In order to fix this problem, we propose a combination of a rectifier and a storage system, where they can operate compatibly under high THD rates (i.e., 125%). Due to high THD values, current–voltage characteristics are not linear-dependent; indeed, because of capacitive effect of the piezoelectric (i.e., lead zirconium titanite) material, harvested power from the material is reduced by nearly a factor of 20% in the output. That also negatively affects the storage on the Li-based battery. In order to compensate, the output waveform of the device, the waveforms, which are received from the energy-harvester device, are first rectified by a full-wave rectifier that has a maximum power point tracking (MPPT) unit. The SOC values prove that almost 40% of the charge is stored in 1.2 s under moderate wind speeds, such as 6.1 m/s. To conclude, a better harvesting performance has been obtained by storing the energy into the Li-ion battery under a current–voltage-controlled boost converter technique.

Keywords: energy harvester; piezoelectric; converter; battery

check for updates

Academic Editors: Mohammed Jama and Addy Wahyudie

Received: 26 August 2025
Revised: 1 October 2025
Accepted: 8 October 2025
Published: 9 October 2025

Citation: Özhan, D.; Kurt, E. An Energy Storage Unit Design for a Piezoelectric Wind Energy Harvester with a High Total Harmonic Distortion. *Processes* **2025**, *13*, 3217. https://doi.org/10.3390/pr13103217

1. Introduction

The main purpose of an energy-harvesting device is to have maximum power from the existing vibration energy in the environment with the help of suitable converter systems. Thus, the conversion of power at its maximum rate becomes the most important task, in addition to the source itself. Harvesting usable energy can be used in the operation of low-powered electronic circuits, mobile devices, sensors, etc. Considering the improvement of wearable electronic devices and wireless communication applications, energy harvesters have received increasing attention world-wide [1–7]. Recently, industry and academia have focused on harvesting energy from mechanical vibrations by using piezoelectric layers due to the high energy density per volume. The efforts for efficient power generation yield to optimization issues in the electrical load, piezoelectric materials, device geometry, and natural frequency since these devices exhibit a hysteresis phenomenon on frequency increase/decrease [8–11]. Energy harvesting conceptually differs from any energy generation in the sense that harvesters basically focus on the lost forms of surrounding stresses, which affect a compact transformation device through sound, vibration, light, temperature, etc., and therefore, a capturing mechanism is indeed activated in any harvesting operation rather than generating energy from a high number of energy sources, such as traditional resources [1]. Therefore, accumulation of a low amount of energy is a vital problem in order to use it when it is required. Frankly speaking, low power ranges such as μW/mW are frequently encountered in these applications. Most of the electrical devices use batteries, creating maintenance problems due to environmental issues or complicated recycling operations. Another important point is that the battery lifetime is short, and that can be increased further by harvesters with ambient sources. Recent advances in wireless and microelectromechanical systems technology have proven that frequency dependence can be neglected by applying additional frequency transforming bodies on small scales [9,12,13], and thereby one can increase the efficiency for different frequency regimes, too. That also helps to make alternative designs for the replacement of conventional batteries. Considering the ultra-low power (i.e., μW range) portable electronic devices, the usage of conventional batteries as power sources is too limited when it is compared to the working life of these devices. Energy harvesters can assist as a self-powered source for portable devices or wireless sensor networks in this respect [7,14–16]. In general, the methods used to obtain electrical energy from mechanical vibrations can be divided into three basic groups: electromagnetic (inductive) [9,17–21], electrostatic (capacitive) [22–24], and piezoelectric [25–31], where piezoelectric is the most convenient in terms of energy density.

Among various harvesting materials, piezoelectricity exhibits pressure electricity through the variation in potential structure inside crystalline material. These materials include Rochelle salt, quartz, tourmaline, barium titanate, etc. When pressure is applied to them in a certain direction, these crystals undergo a deformation; in addition, when an electric field E is applied to the terminals of these materials, as a converse effect, a vibration occurs in the material itself. When a converse effect is applied, it can be used as an actuator, and thereby, the direct effect can be used as a sensor or energy transducer in that context [32]. According to the detailed works, energy densities of piezoelectric energy harvesters are three or five times higher than those of electrostatic or electromagnetic harvesters [9,33]. With their compact nature, piezoelectric harvesters are widely used for wireless applications in the industry and daily life [34–37]. The main reasons for the wide usage cases are easy installation and maintenance [38]. Following the advances in material engineering, the production of piezoelectric materials has become cheaper compared to the past decades. This reality in the market also enables the piezoelectric harvesters to find a good place in addition to thermoelectric generators and solar photovoltaics [39]. Although piezoelectric components generate less energy, the output can be conveyed to an electronic device directly or a storage unit [40]. Harvested energy can be usable with converters; however, their efficiency should be enough to proceed and to avoid energy losses. Therefore, by using the outputs of three piezoelectric layers, a full bridge rectifier depicted in Figure 1 has been designed and used in an energy storage unit (ESU).

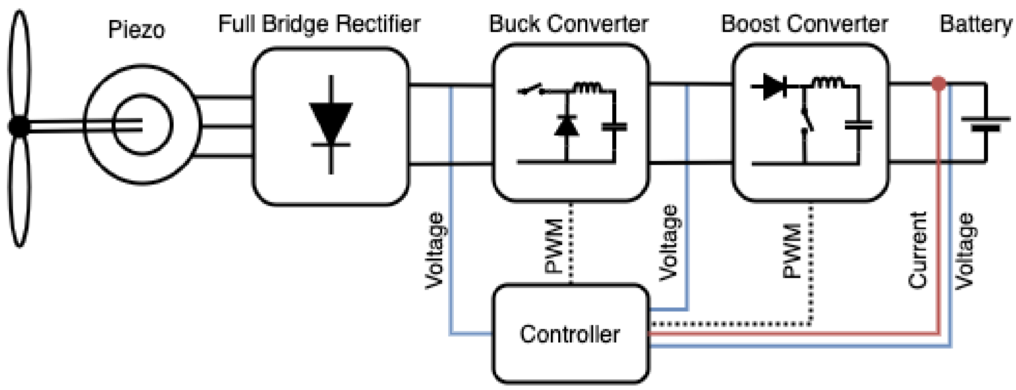


Figure 1. A general circuitry of the energy storage unit (ESU).

When the wind puts the turbine into rotation, electrical signals from the terminals are created by connecting the harvester body to the piezoelectric material. The signal obtained by vibration of the piezoelectric material is mostly similar to a sinusoidal signal; therefore, a straightening operation will be required before energy can be stored. The generator impedance and receiver impedance should be identical for the maximum power transfer. Although waveforms have high impedances, the receivers and batteries do not have such high impedance values. Strictly speaking, an impedance mismatch exists between the turbine and the receiver. A rectifier and a dc-dc converter are quite common to eliminate impedance mismatch in this regard [41]; however, waveforms have highly noisy behavior. Therefore, high THD causes certain power loss at the output of the piezoelectric wind energy harvester (PWEH) [42–44]. Indeed, harmonics in linear motions or rotating systems can have different causes. According to the literature, mostly mechanical stresses in the system or repulsion effects relating to the magnetic components, such as magnets, relays, cores, etc., can cause these harmonic problems. Even in a well-designed machine, there can always be harmonic issues if the magnetic field variation is obtained by elastic bodies [1,2,7,43].

The paper is organized as follows: Section 2 gives detailed information on the harvester itself and the designed ESU. Section 3 presents the experimental and theoretical details of the combined PWEH and ESU systems. Finally, the concluding remarks and future works are discussed in Section 4.

2. Materials and Methods

The piezoelectric wind energy harvesters (PWEHs) provide very low power values at milliwatts (mW) or microwatts (μW), like some other vibration generators in the literature. Such vibration generators cannot maintain large power outputs during operation [45]. The system we designed and implemented with PWEHs contains many harmonics that show a very high THD due to nonlinear effects; the current and voltage characteristics are not linear, which reduces the energy production efficiency of this source. In this article, a PWEH is concentrated on a general control circuit to obtain maximum power and store this energy in a system that contains many harmonics, high THD, and nonlinear effects. In order to improve these, an ESU system is designed with a control circuit. This article numerically analyzes the waveforms that use the piezoelectric signals, the quality of which is improved with the proposed system, to be rectified and then used for the feeding of low-power electronic systems with high efficiency, or to be stored when necessary. Nonlinearity can arise from different reasons, including experimental noise; however, analyzing the system in a numerical manner provides us with correct information on the extent to which the reason for nonlinearity stands in the motion. Waveform analyses are critical for ensuring a continuous and stable energy supply for low-power systems. These analyses aim to minimize fluctuations in the energy transferred to the storage unit, resulting in a more stable DC power supply. This allows low-power devices such as sensors, monitoring circuits, and portable microcontroller-based systems to efficiently meet their energy needs.

2.1. Modeling of Harvester Design

Since the PWEH has 3 piezoelectric materials with various masses, they yield to various natural frequencies. The layers have the same length as the mass of 1.4 g and a force constant of 380 N/m. Physically, a permanent magnet (PM) stands on the shaft, rotating under low wind speeds. Other permanent magnets are mounted at the ends of each piezoelectric layer. When the rotating magnet and the other permanent magnet meet, the magnets repel each other, causing the piezoelectric layer to vibrate. This rotation causes the PMs to be repelled, and 3 piezoelectric materials vibrate with a phase shift of 120 degrees. The PM on the shaft and the other PMs on the layers are not physically contacted, and thus, that improves the durability and lifespan of the piezoelectrics, as seen in Figure 2a,b. According to the experiments with the wind tunnel, the harvested power p = 0.2 mW was reached under low wind speeds, such as v = 1.75 m/s. In addition, a large amount of the power was stored in the battery.

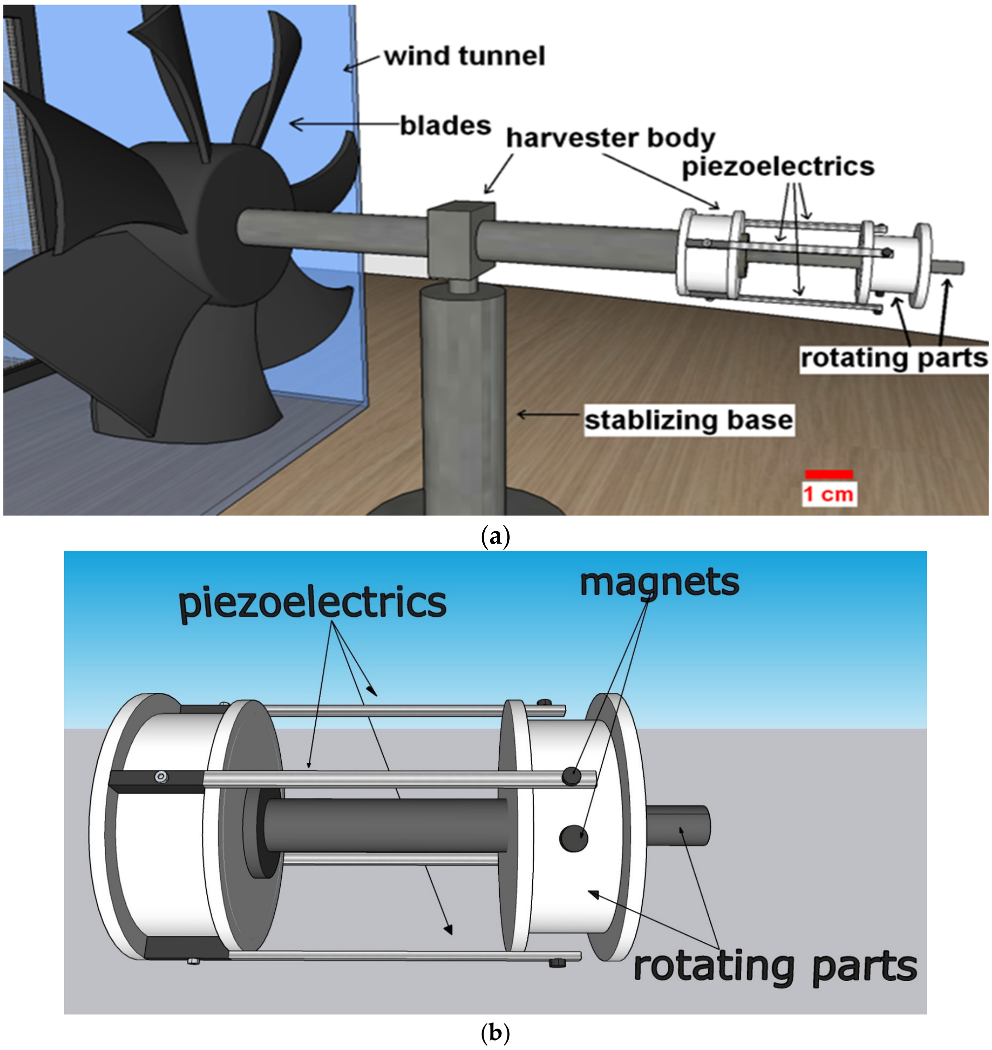


Figure 2. (**a**) PWEH unit with piezoelectric materials at the tip of the rotating parts; (**b**) a close look at the piezoelectric and magnet components.

2.2. Topology of the Circuit

Figure 3 shows the general circuitry of the proposed ESU and controller attached to the terminals of PWEH. Initially, the generated voltages are transmitted to the rectifier circuit; afterwards, the rectifier output is forwarded to a dc-dc converter that has buck/boost characteristics. A battery is added at the end of the overall system, as seen in Figure 3. Also, at this point, a state of charge (SOC) is controlled, too. In the literature, there are some techniques for the estimation of the maximum power point (MPP). According to Table 1, the battery with Li-ion has 0.1 Ah under the maximum value of 3.6 V, although it has some environmental problems and recyclability issues. However, in our system, other battery types can also be used when the battery impedance is considered relevant to the output of circuitry. In addition, although the overall system consists of many components, they are very cheap due to the low-power operation of the system.

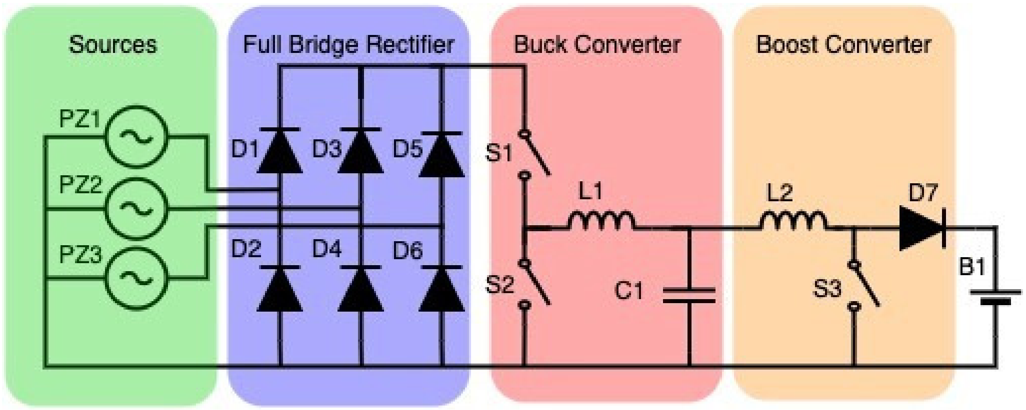


Figure 3. General circuit diagram of the combination of PWEH and ESU.

Table 1. Parameters of the converter units.

Title 1	Buck Converter	Boost Converter
Inductance (L)entry 1	1 mH data	1 mH data
Capacitance (C)entry 2	1 mF data	1 mF data 1
Switching Frequency (f)	10 kHz	10 kHz
PI Control (P-I)	200–300	200–300
Sample Time (Tss)	1×10^{-6} s	1×10^{-6} s
Battery	Li-ion, 0.1 Ah, 3.6 V	Li-ion, 0.1 Ah, 3.6 V

MPP can be identified by half of the open-circuit voltage ($V_{oc}/2$) [46]. In the present work, the MPPT scheme is implemented for the PWEH with a power scale of µW. The proposed MPPT scheme operates well, with a good efficiency value for such a high THD-generating device.

2.3. Controller

The main circuitry consists of 4 block diagrams (Figure 4): The initial one is the PWEH device itself. Sample harvested waveforms are shown as an input to the rectifier in Figure 5. Piezoelectric materials are 120 degrees from each other for the electrical phase variation; therefore, they produce different waveforms depending on their natural frequencies. The second block is the rectifier. It is full-bridge rectifiers that convert AC waveforms to a DC waveform. The third diagram is the buck converter, where the full-rectified waveform (V_{rect}) is controlled by the buck converter for the MPPT aim. According to the literature, there exist a few techniques to estimate and track the MPP. Hill-climbing (HC) and fractional open-circuit voltage (FOCV) methods are frequently used techniques [47,48]. The last block is a boost converter, where current and voltage are controlled for the battery's SOC. The rectifier works as an open-circuit (V_{oc}). The fractional open-circuit voltage (FOCV) method is based on determining the V_{OC} at which maximum power is delivered. Then, the MPPT obtains the V_{oc} value. This is also stored in a capacitor, and then it is utilized as the reference voltage for V_{rect}. Note that the MPPT governs the DC-DC converter for the regulation of the output waveform in the vicinity of V_{oc} by monitoring the change in V_{rect}. In the last part, a lithium-ion battery operates as a rechargeable battery type, where lithium ions move from the negative potential to the positive one during the discharge process [49]. These batteries are popular for portable electronics as they have the best energy-to-weight ratios, low self-discharge rate, and high open-circuit voltage [50].

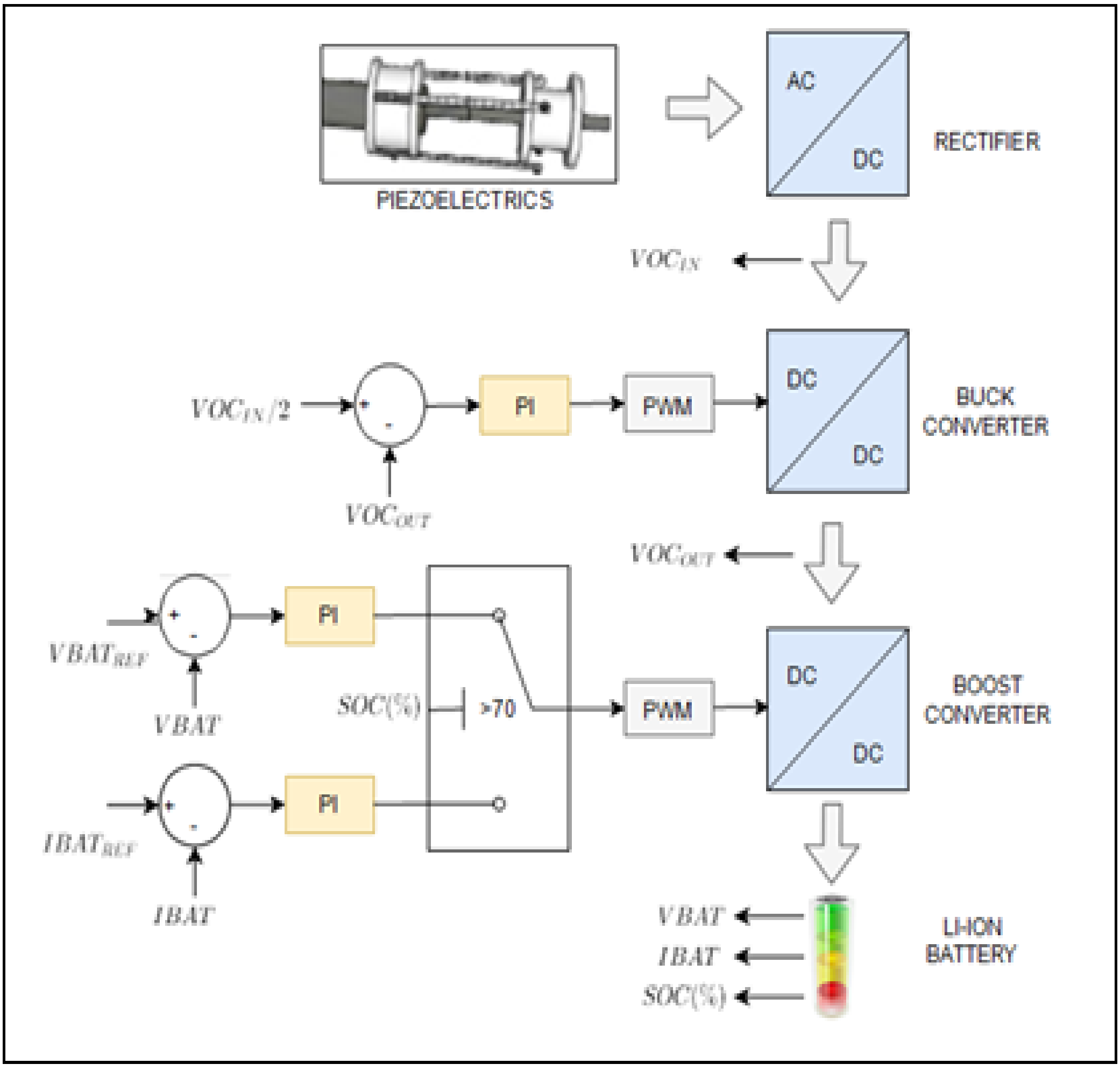
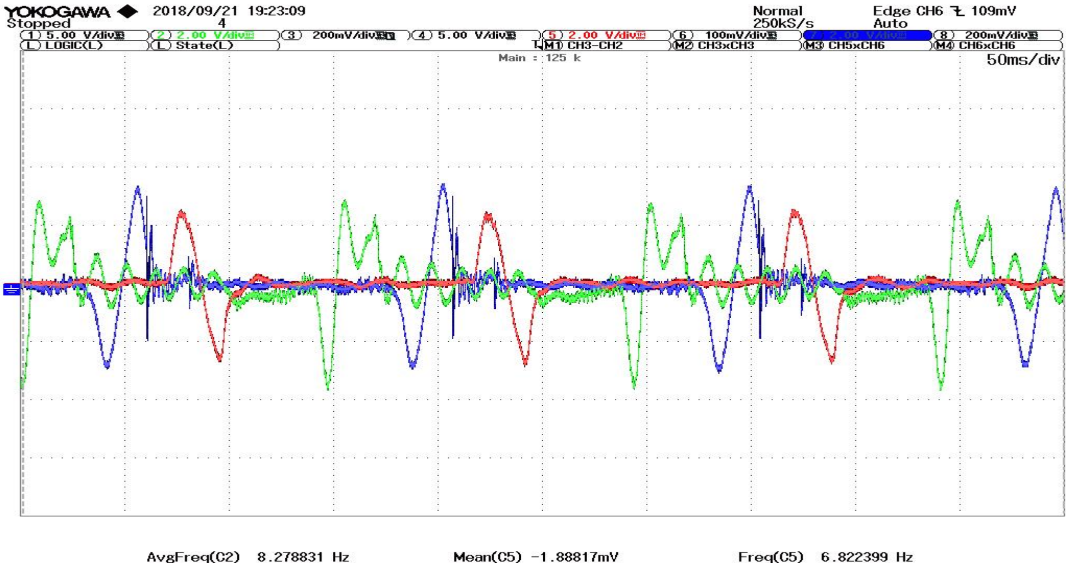
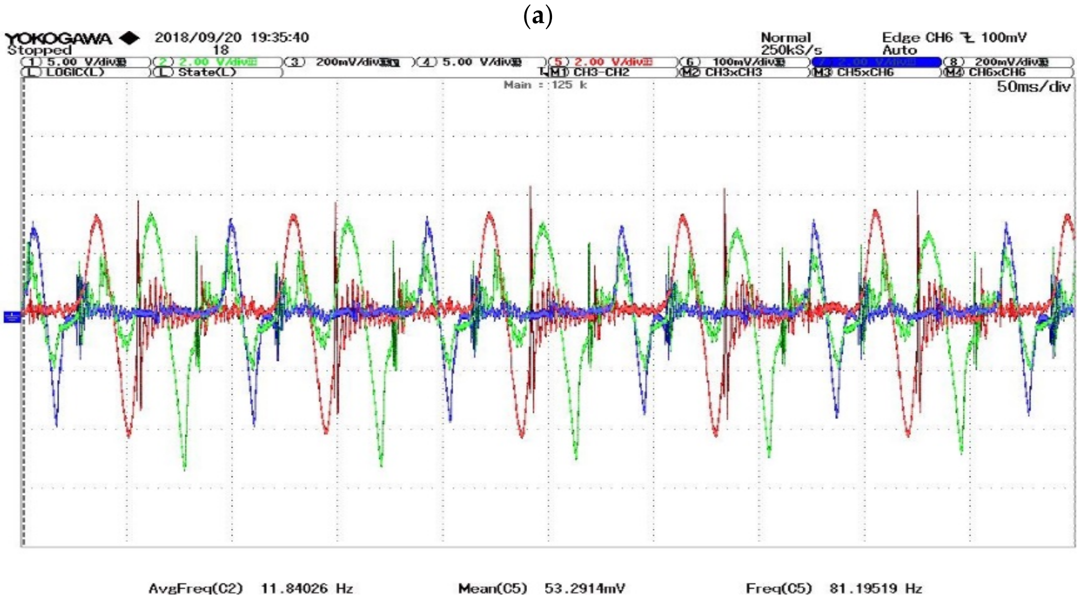


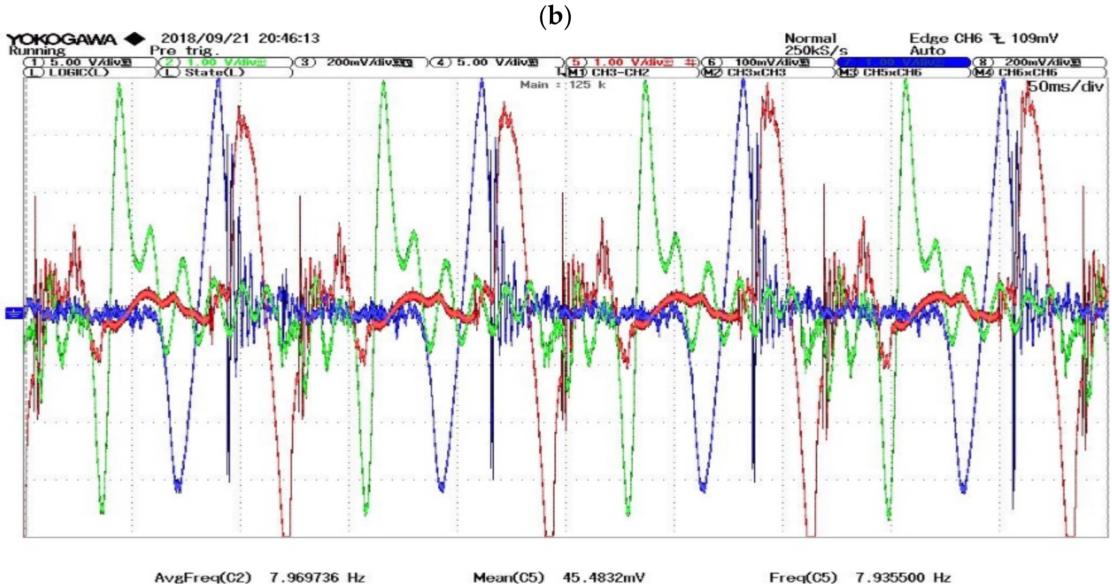
Figure 4. General control structure of the proposed system.



(**a**)



(**b**)



(**c**)

Figure 5. Real oscilloscope waveforms (i.e., colors correspond to three phases) of piezoelectric layers: (**a**) wind speeds at 2.7 m/s; (**b**) 3.5 m/s; and (**c**) 6.1 m/s.

3. Results

According to the setup in Figure 2, the harvester operates in a wind tunnel. Each layer has a dimension of 41.3 × 4.7 × 1.5 mm. In addition, capacitance and stiffness values are C = 12 nF and α = 61 N/m, respectively. Data acquisition has been made by an NI USB-6250 card with 16 analog inputs. It can record multiple data sets if desired. Each waveform from the harvester layers is forwarded to the circuit blocks. When the system is operated at varying wind speeds, the values of the signals obtained from the piezoelectric layers change with the speed. It has been observed that the system does not work well when the wind speed is greater than 8 m/s. Here, the magnet on the rotating shaft and the magnets at the ends of the piezo layers vibrate at higher speeds, resulting in additional mechanical vibration, and the reaction of magnets at such a high speed does not generate much electricity since the displacement of the tip of the layers stays small. In some cases, it has been observed that these high-speed vibrations yield to the magnet-sticking process, and thereby, they may destroy the piezoelectric layers by breaking them. It has been observed that the mechanical design and sensitivity of the system work more smoothly and efficiently at wind speeds between 3 and 7 m/s. The efficient operation of the designed system at light and medium wind speeds can be considered an advantage. If the system is used as a primary or secondary energy source, it means that it can produce energy even at a very low wind speed and can be stored when desired. Figure 5 shows the state of the piezoelectric signals with the speed when the system is operated at different wind-tunnel speeds (2–8 m/s).

A Yokogawa-type oscilloscope has also been used in order to follow the outputs of the circuit. Experimental waveforms are shown in Figure 5, and the MatLab form is also shown in Figure 6. The waveforms obtained from the three layers appear to have different nonlinear characteristics. Although the device has three identical layers, the magnets at the ends of the piezoelectric materials influence the natural frequencies of the layers. The high-frequency components have the lowest amplitude and do not contribute significantly to the power output from these waveforms. It is seen that a high (i.e., around 130%) THD value can be the main problem for the rectification. This condition increases the sub-harmonic and super-harmonic ingredients of the waveforms, and storage of energy is not possible without using an efficiently controlled rectification.

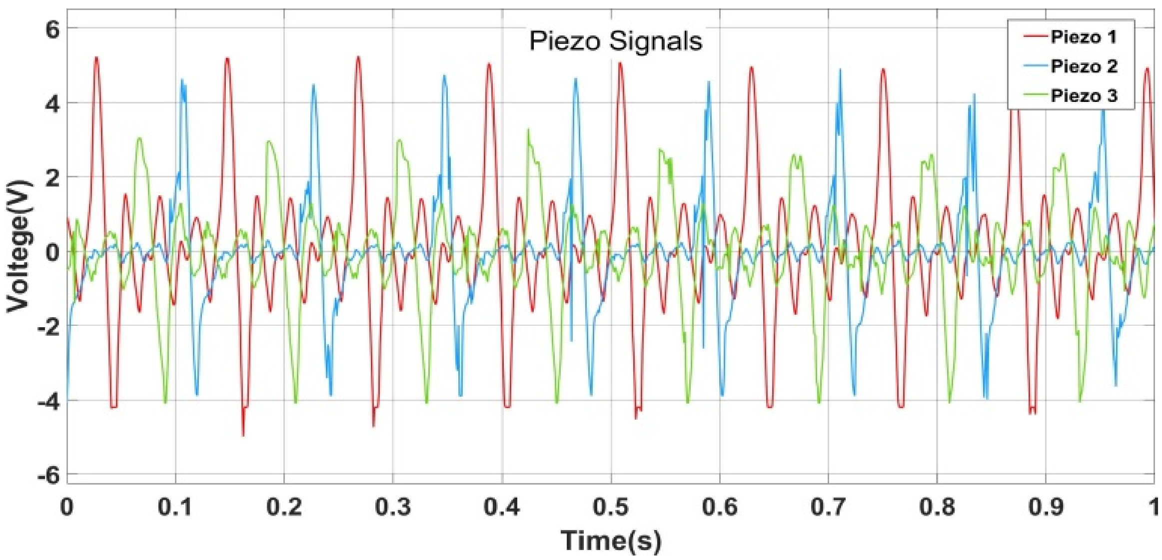


Figure 6. Waveforms from DAQ card for MatLab process (wind speeds at 3.5 m/s).

In Figure 7, the rectified waveforms after the rectifier and buck converter are shown. Note that, although the voltage values are around 3.5 V and 1.5, the current values are low; therefore, the power harvested from such systems is in the order of µW scale.

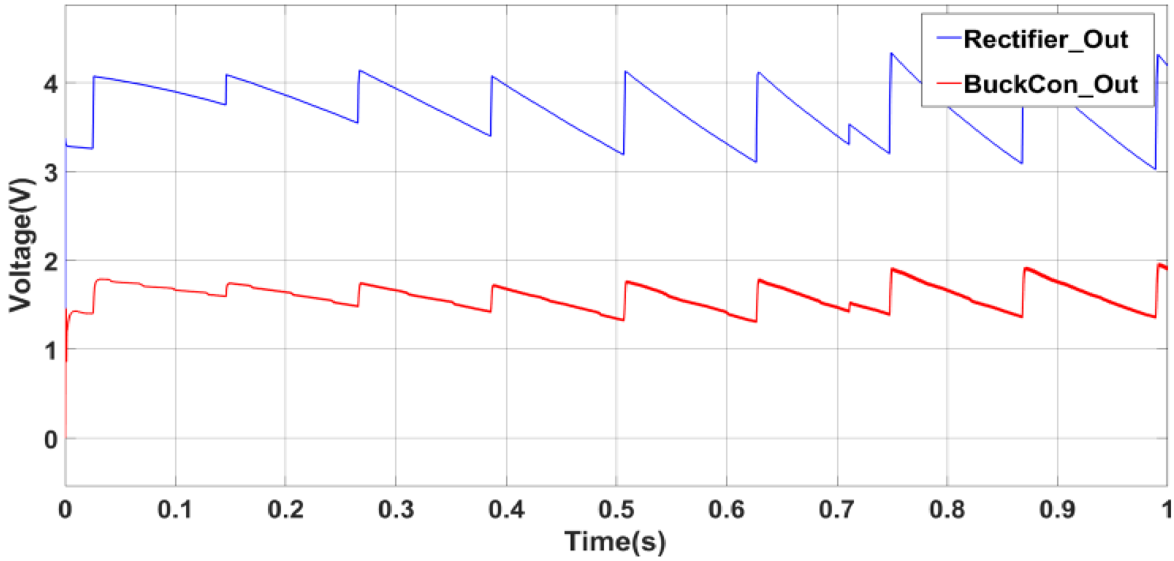
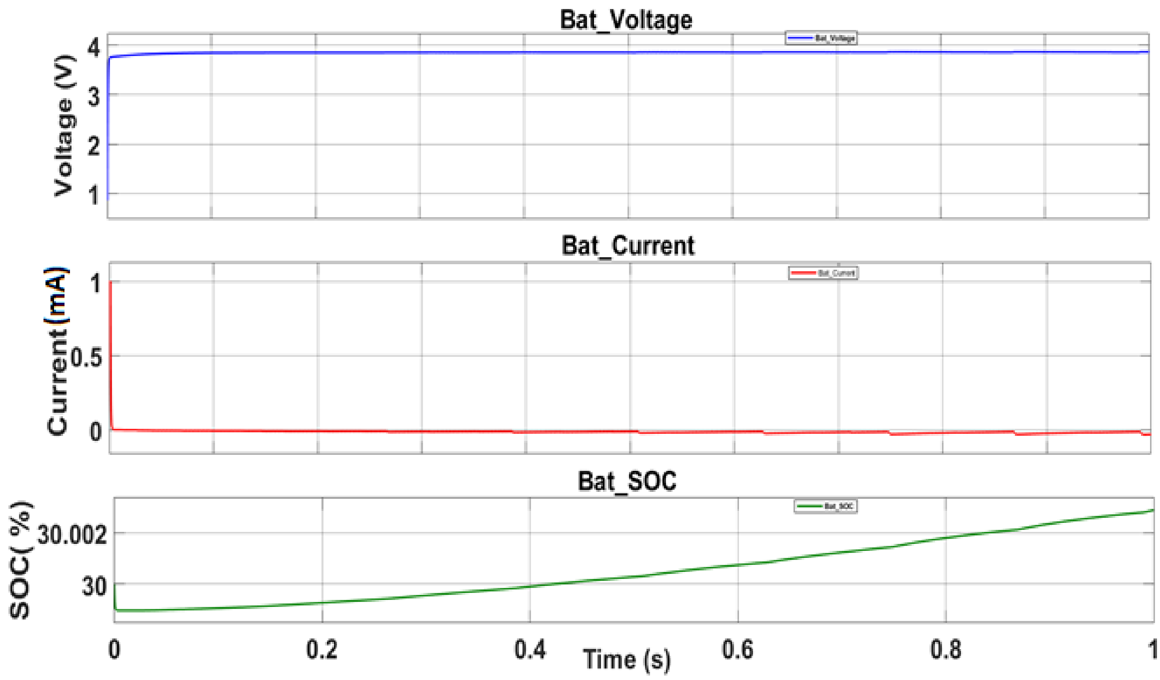


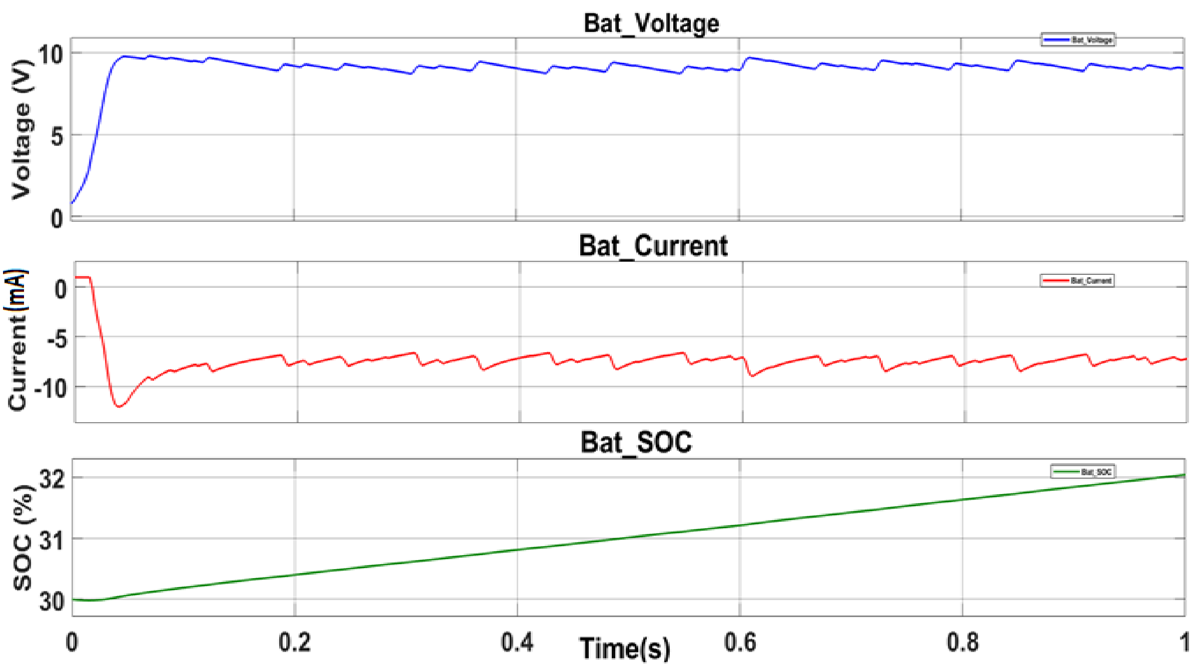
Figure 7. Real piezo output signals.

The battery voltage, current, and SOC values are shown in multiple plots of Figure 8a–c. It is clear that while the current decrease over time due to the storage, the controller SOC value increases slowly. In a very short time interval, the output voltage is stabilized for storage, which is also important for the stability of the circuit. By comparing the plots in Figure 8a–c, it has been understood that the battery current strictly depends on the rotation speed; indeed, higher rotations reasonably yield higher battery currents.

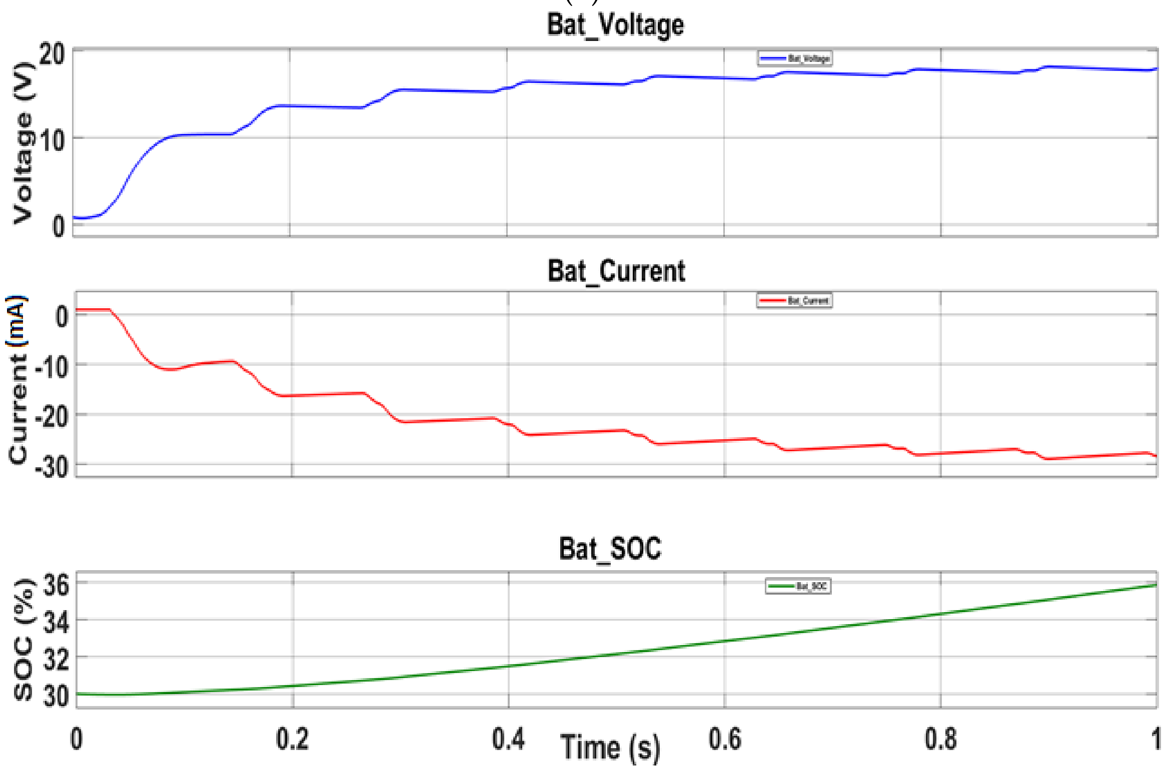


(**a**)

Figure 8. *Cont.*



(**b**)



(**c**)

Figure 8. Battery-charging results for the speeds of (**a**) 2.7 m/s, (**b**) 3.5 m/s, and (**c**) 6.1 m/s.

4. Discussion

The present work focuses on a controlled storage system for a piezoelectric three-phase device. The circuit has a Li-ion battery system for storage. Waveforms observed in our previous study proved that the waveforms coming from piezo plates had high THD. Thus, the first purpose should be decreasing harmonics in the rectification before the battery-charging procedure. For this, the waveforms received directly from the piezoelectric plates are supplied to the buck converter after the rectification to fulfill the $V_{oc}/2$ control condition. The output signals are filtered with the help of the boost converter, and with the current–voltage and battery charge status (SOC) values of the battery; then, the battery has been charged. The system was operated at different wind speeds, and the optimal efficiency was analyzed. The system was found to operate most efficiently at light and medium wind speeds. Due to this operating range, we believe that the system can be easily used in applications that can meet the energy needs of the system, or in some of the circuits that require small power. We propose this circuitry to optimize the output energy generation of the proposed wind energy harvester; however, that circuitry can also be used for any piezoelectric-based energy-harvesting device with highly distorted outputs.

Author Contributions: Conceptualization, E.K.; Methodology, D.Ö. and E.K.; Software, D.Ö.; Validation, D.Ö.; Formal analysis, D.Ö.; Investigation, E.K.; Resources, D.Ö. and E.K.; Data curation, D.Ö.; Writing – original draft, D.Ö.; Writing – review & editing, E.K.; Visualization, D.Ö. and E.K.; Supervision, E.K.; Project administration, E.K.; Funding acquisition, E.K. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the supports of Gazi University—Scientific Research Project Unit under the Project no. BAP 07/2010-01 and The Scientific and Technological Research Council of Turkey (TUBITAK) under grant EEEAG-114E017.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bizon, N.; Tabatabaei, N.M.; Blaabjerg, F.; Kurt, E. (Eds.) *Energy Harvesting and Energy Efficiency: Technology, Methods, and Applications*; Springer International Publishing: Cham, Switzerland, 2017. [CrossRef]
2. Harne, R.L.; Wang, K. A review of the recent research on vibration energy harvesting via bistable systems. *Smart Mater. Struct.* **2013**, *22*, 023001. [CrossRef]
3. Toprak, A.; Tigli, O. Piezoelectric energy harvesting: State-of-the-art and challenges. *Appl. Phys. Rev.* **2014**, *1*, 031104. [CrossRef]
4. Siddique, A.R.M.; Mahmud, S.; Van Heyst, B. A comprehensive review on vibration based micro power generators using electromagnetic and piezoelectric transducer mechanisms. *Energy Convers. Manag.* **2015**, *106*, 728–747. [CrossRef]
5. Xie, Z.; Kwuimy, C.A.K.; Wang, Z.; Huang, W. A piezoelectric energy harvester for broadband rotational excitation using buckled beam. *AIP Adv.* **2018**, *8*, 015125. [CrossRef]
6. Singla, P.; Sarangi, S.R. A survey and experimental analysis of checkpointing techniques for energy harvesting devices. *J. Syst. Archit.* **2022**, *126*, 102464. [CrossRef]
7. Lin, W.; Wei, Y.; Wang, X.; Zhai, K.; Ji, X. Study on human motion energy harvesting devices: A review. *Machines* **2023**, *11*, 977. [CrossRef]
8. Zheng, Y.; Zhang, Z.; Jiang, X.; Zhao, Y.; Luo, Y.; Wang, Y.; Wang, Z.; Zhang, Y.; Liu, X.; Fang, B. A Comprehensive Review on Iron-Based Sulfate Cathodes for Sodium-Ion Batteries. *Nanomaterials* **2024**, *14*, 1915. [CrossRef]
9. Uchino, K. Piezoelectric energy harvesting systems—Essentials to successful developments. *Energy Technol.* **2018**, *6*, 829–848. [CrossRef]
10. Paul, T.; Maiti, S.; Mukherjee, U.; Mondal, S.; Sahoo, A.; Chattopadhyay, K.K. Cube shaped FAPbBr3 for piezoelectric energy harvesting devices. *Mater. Lett.* **2021**, *301*, 130264. [CrossRef]
11. Khasawneh, M.A. Energy harvesting devices in pavement structures. *Innov. Infrastruct. Solut.* **2025**, *10*, 183. [CrossRef]
12. Friswell, M.I.; Adhikari, S. Sensor shape design for piezoelectric cantilever beams to harvest vibration energy. *J. Appl. Phys.* **2010**, *108*, 014901. [CrossRef]
13. Luo, S.-H.; Wang, Y.; Liu, Q.; Li, P.; Wang, Z.; Yan, S.; Teng, F. Recent progress and perspective of cathode recycling technology for spent $LiFePO_4$ batteries. *J. Ind. Eng. Chem.* **2024**, *133*, 65–73. [CrossRef]
14. Adhikari, S.; Friswell, M.A.; Inman, D. Piezoelectric energy harvesting from broadband random vibrations. *Smart Mater. Struct.* **2009**, *18*, 115005. [CrossRef]
15. Kim, H.S.; Kim, J.-H.; Kim, J. A review of piezoelectric energy harvesting based on vibration. *Int. J. Precis. Eng. Manuf.* **2011**, *12*, 1129–1141. [CrossRef]

16. Jin, K.; Yan, X.; Li, J.; Zhou, M.; Fu, K.; Wei, X.; Meng, F.; Liu, J. Recent progress in aqueous underwater power batteries. *Discov. Appl. Sci.* **2024**, *6*, 441. [CrossRef]
17. Nechibvute, A.; Chawanda, A.; Luhanga, P. Piezoelectric energy harvesting devices: An alternative energy source for wireless sensors. *Smart Mater. Res.* **2012**, *2012*, 853481. [CrossRef]
18. Glynne-Jones, P.; Tudor, M.; Beeby, S.; White, N. An electromagnetic, vibration-powered generator for intelligent sensor systems. *Sens. Actuators A Phys.* **2004**, *110*, 344–349. [CrossRef]
19. Torah, R.N.; Tudor, M.J.; Patel, K.; Garcia, I.N.; Beeby, S.P. Autonomous low power microsystem powered by vibration energy harvesting. In Proceedings of the SENSORS, 2007 IEEE, Atlanta, GA, USA, 28–31 October 2007.
20. Ambrożkiewicz, B.; Litak, G.; Wolszczak, P. Modelling of electromagnetic energy harvester with rotational pendulum using mechanical vibrations to scavenge electrical energy. *Appl. Sci.* **2020**, *10*, 671. [CrossRef]
21. Płaczek, M.; Dulat, Ł. Supporting the Design of Systems for Energy Recovery from Mechanical Vibrations Containing MFC Piezoelectric Transducers. *Appl. Sci.* **2025**, *15*, 5530. [CrossRef]
22. von Büren, T.; Tröster, G. Design and optimization of a linear vibration-driven electromagnetic micro-power generator. *Sens. Actuators A Phys.* **2007**, *135*, 765–775. [CrossRef]
23. Mitcheson, P.D.; Miao, P.; Stark, B.; Yeatman, E.; Holmes, A.; Green, T. MEMS electrostatic micropower generator for low frequency operation. *Sens. Actuators A Phys.* **2004**, *115*, 523–529. [CrossRef]
24. Ghashami, G.; Mahnama, M.; Zand, M.M.; Allaei, S.M.V.; López-Suárez, M. Energy harvesting from mechanical vibrations: Self-rectification effect. *Phys. Chem. Chem. Phys.* **2023**, *25*, 14400–14405. [CrossRef]
25. Khbeis, M.; McGee, J.; Ghodssi, R. Development of a simplified hybrid ambient low frequency, low intensity vibration energy scavenger system. In Proceedings of the TRANSDUCERS 2009–2009 International Solid-State Sensors, Actuators and Microsystems Conference, Denver, CO, USA, 21–25 June 2009.
26. Erturk, A. Electromechanical Modeling of Piezoelectric Energy Harvesters. Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, 2009.
27. Choi, W.J.; Jeon, Y.; Jeong, J.-H.; Sood, R.; Kim, S.G. Energy harvesting MEMS device based on thin film piezoelectric cantilevers. *J. Electroceram.* **2006**, *17*, 543–548. [CrossRef]
28. Sodano, H.A.; Inman, D.J.; Park, G. Comparison of piezoelectric energy harvesting devices for recharging batteries. *J. Intell. Mater. Syst. Struct.* **2005**, *16*, 799–807. [CrossRef]
29. Bahrami, A.; Motaei, F. A review of phononic-crystal-based energy harvesters. *Prog. Energy* **2024**, *7*, 012002. [CrossRef]
30. Mastouri, H.; Ennawaoui, A.; Remaidi, M.; Sabani, E.; Derraz, M.; El Hadraoui, H.; Ennawaoui, C. Design, Modeling, and Experimental Validation of a Hybrid Piezoelectric–Magnetoelectric Energy-Harvesting System for Vehicle Suspensions. *World Electr. Veh. J.* **2025**, *16*, 237. [CrossRef]
31. Wang, H.; Huang, X.; Li, Z.; Fang, L. Design of a Portable Integrated Fluid–Structure Interaction-Based Piezoelectric Flag Energy-Harvesting System. *Fluids* **2025**, *10*, 121. [CrossRef]
32. Mitcheson, P.D.; Green, T.C.; Yeatman, E.M. Power processing circuits for electromagnetic, electrostatic and piezoelectric inertial energy scavengers. *Microsyst. Technol.* **2007**, *13*, 1629–1635. [CrossRef]
33. Chopra, I. Review of state of art of smart structures and integrated systems. *AIAA J.* **2002**, *40*, 2145–2187. [CrossRef]
34. Priya, S. Advances in energy harvesting using low profile piezoelectric transducers. *J. Electroceram.* **2007**, *19*, 167–184. [CrossRef]
35. Fu, H.; Yeatman, E.M. A miniaturized piezoelectric turbine with self-regulation for increased air speed range. *Appl. Phys. Lett.* **2015**, *107*, 243905. [CrossRef]
36. Uchino, K.; Ishii, T. Energy flow analysis in piezoelectric energy harvesting systems. *Ferroelectrics* **2010**, *400*, 305–320. [CrossRef]
37. Renaud, M.; Fiorini, P.; van Schaijk, R.; van Hoof, C. Harvesting energy from the motion of human limbs: The design and analysis of animpact-based piezoelectric generator. *Smart Mater. Struct.* **2009**, *18*, 035001.
38. Uzun, Y.; Kurt, E. Performance exploration of an energy harvester near the varying magnetic field of an operating induction motor. *Energy Convers. Manag.* **2013**, *72*, 156–162. [CrossRef]
39. Song, Y.; Yang, C.H.; Hong, S.K.; Hwang, S.J.; Kim, J.H.; Choi, J.Y.; Ryu, S.K.; Sung, T.H. Road energy harvester designed as a macro-power source using the piezoelectric effect. *Int. J. Hydrogen Energy* **2016**, *41*, 12563–12568. [CrossRef]
40. Ranjit, P.; Thakur, A.K. ENERGY HARVESTING & STORAGE. In *Energy Harvesting Technologies for Powering WPAN and IoT Devices for Industry 4.0 Up-Gradation*; Nova Science Publishers: Hauppauge, NY, USA, 2020.
41. Uzun, Y.; Demirbas, S.; Kurt, E. Implementation of a new contactless piezoelectric wind energy harvester to a wireless weather station. *Elektron. Ir Elektrotechnika* **2014**, *20*, 35–39.
42. Kim, H.; Priya, S.; Stephanou, H.; Uchino, K. Consideration of impedance matching techniques for efficient piezoelectric energy harvesting. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2007**, *54*, 1851–1859. [CrossRef]
43. Kurt, E.; Özhan, D.; Bizon, N.; Lopez-Guede, J.M. Design and implementation of a maximum power point tracking system for a piezoelectric wind energy harvester generating high harmonicity. *Sustainability* **2021**, *13*, 7709. [CrossRef]

44. Touairi, S.; Ghalim, N.; Ouaomar, H.; Kouider, N. Optimization strategies for cost-effectiveness in piezoelectric energy harvesting systems. *Int. J. Dyn. Control* **2025**, *13*, 156. [CrossRef]
45. Du, S.; Jia, Y.; Arroyo, E.; Seshia, A.A. Rectified Output Power Analysis of Piezoelectric Energy Harvester Arrays under Noisy Excitation. In Proceedings of the 17th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS 2017), Kanazawa, Japan, 14–17 November 2017.
46. Kurt, E.; Cottone, F.; Uzun, Y.; Orfei, F.; Mattarelli, M.; Özhan, D. Design and implementation of a new contactless triple piezoelectrics wind energy harvester. *Int. J. Hydrogen Energy* **2017**, *42*, 17813–17822. [CrossRef]
47. Kong, N.; Ha, D.S. Low-power design of a self-powered piezoelectric energy harvesting system with maximum power point tracking. *IEEE Trans. Power Electron.* **2012**, *27*, 2298–2308. [CrossRef]
48. Chowdary, G.; Singh, A.; Chatterjee, S. An 18 nA, 87% efficient solar, vibration and RF energy-harvesting power management system with a single shared inductor. *IEEE J. Solid-State Circuits* **2016**, *51*, 2501–2513. [CrossRef]
49. Chew, Z.J.; Zhu, M. Adaptive maximum power point finding using direct V OC/2 tracking method with microwatt power consumption for energy harvesting. *IEEE Trans. Power Electron.* **2017**, *33*, 8164–8173. [CrossRef]
50. Sinkaram, C.; Asirvadam, V.S.; Nor, N.B.M. Capacity study of lithium ion battery for hybrid electrical vehicle (HEV) a simulation approach. In Proceedings of the 2013 IEEE International Conference on Signal and Image Processing Applications, Melaka, Malaysia, 8–10 October 2013.