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Original Research Article

Piezoelectric Floor Mat Systems for Sustainable Energy Harvesting

Lanre Olatomiwa[1*], Auta Husseini Nsunya[1], Harrison O. Idakwo[2], Ademoh A. Isah[1], James G. Ambafi[1], Isiyaku Saleh[1], Angbas Arigu Daniel[1]

[1]Department of Electrical & Electronics Engineering, Federal University of Technology, Minna, PMB 65, Minna, Nigeria
[2]Department of Electrical & Electronics University of Maiduguri, Maiduguri, Nigeria

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***Corresponding author:** Lanre Olatomiwa
Department of Electrical & Electronics Engineering, Federal University of Technology, Minna, PMB 65, Minna, Nigeria

Abstract

This study examines the suitability of piezoelectric floor mat systems for harvesting energy in high traffic areas like the student centers. The study is aimed at solving the problems of small energy production, toxic materials and the ability to scale up current piezoelectric energy harvesting systems. The study involves experimental simulation of using 40 piezo transducers, a 2W02G rectifier, two 2F, 5.5V super capacitors for energy storage, an ND0603PC booster amplifier for output regulation and two LiPo batteries in series, to supply stable power to a case study Centre. Both the supporting circuit diagram and MATLAB/Simulink simulation were utilized to show that this system works well for independent power generation. Simulations and tests on circuits reveal that the system delivers an average output power greater than the required standard, 400–600 μW per step versus 134.2 μW per step. Rectifying the energy from 1,000 steps yields AC voltages varying from 20–80V which are then changed to DC at 18–75V. At the beginning, the super capacitors charge with 5–6V to last for 10–30 seconds before leveling off at 3.7–5.5V and the LiPo batteries provide about 5–20 mAh after being active for 10 minutes. Trials show that the device produces constant electricity under various stress tests, showing good conversion, storage and release of energy for powering small electronic devices. The results confirm that piezoelectric floor mats can be used affordably to produce energy anywhere in busy areas, thereby aiding efforts to make urban environments and the planet more sustainable. In the future, more experiments and improvements are required for deploying the technology on a wider scale.

Keywords: Piezoelectricity, energy harvesting, floor mats, sustainable energy, kinetic energy, renewable energy.

1. INTRODUCTION

Electricity supply shortages in Nigeria is an ongoing issue, leading to a range of problems including low access to healthcare, educational, and technological services [1]. Lack of access to electricity also implies limited opportunity to grow economically, leading to cycles of poverty that have not yet been resolved. Access to reliable, affordable, and modern electricity services is critical to achieving the universally adopted Sustainable Development Goal of quality education SDG 4 [2], which is a social service that depend on access to electricity in schools. In the education sphere, access to electricity enables lighting and extended studying hours; facilitation of information, communication and technology (ICT); enhanced staff retention and teacher training; among other benefits.

Epileptic power supply has become a concern in many higher educational institutions (HEIs) in Nigeria, especially during the rainy seasons, when there is considerable drop in electricity supply. This has hindered students from reading from their phones and laptops resulting in low academic performance, considering the fact that most academic materials are now given in softcopies. One outstanding solution to this problem is the use of piezoelectric footmat. These mats generate energy through the force of pressure, such as a person stepping on them. This energy can then be stored in rechargeable batteries for later use. By distributing these mats in areas that lack electricity, where a number of people walk through, it is possible to generate and store energy from even remote areas.

The justification for the this study is specifically to gain insight into an innovative, cost-effective and sustainable approach to tackling the growing issue of energy access and availability in our university community-Federal University of Technology, Minna, Nigeria and other places. This research discusses the technical details and practical applications of applying piezoelectric footmat, and by exploring its detailed concepts, and further the understanding of the potential for generating electricity in places without adequate access to a reliable electricity. By analysing the material and structural components of this foot mat and studying the resulting energy output, we can gain an understanding of the best ways to utilize and optimize the energy generation for other use.

The major contribution of this study therefore, is to assess the potential of piezoelectric device in powering basic electronics appliance at a student's relaxation centre in the Engineering Complex of Federal University of Technology Minna, Nigeria. To achieve this aim, there is need for location study of high traffic areas within the considered building, assess the potential of electricity generation using piezoelectric material, followed by development of piezoelectric tiles deployment strategy and finally design of low power converter (rectifier/inverter) and energy storage circuit for storing the harvested energy for the purpose of powering electronic devices at the relaxation Centre. The study is expected to improve power supply in the considered building, especially in the relaxation centre of the building to power basic electrical appliances such as TV, decoder, mobile phone chargers, laptops etc, for the purpose of enhancing student learning thus resulting in better academic performance.

The manuscript is structured as follows: Section 1, covers the introduction to the study while section 2 gives the theoretical background and review of related works. Section 3 details the study methodology and section 4 gives the result and discussion. Lastly, section 5 brings together the main findings and offers conclusions to the study.

2. LITERATURE REVIEW

2.1 Theoretical Review

- **Types of Piezoelectric Materials**

Piezoelectric materials are categorized into natural and synthetic types, each with unique properties and applications. Naturally, quartz and tourmaline have strong piezoelectric effects and that's why they were used centuries ago in watches. Enhanced performance in sensors, actuators and energy harvesting is made possible by the use of Lead Zirconate Titanate (PZT), Barium Titanate (BT) and Polyvinylidene Fluoride (PVDF) synthetic materials. Another important trend involves finding lead-free materials and among them are Potassium Sodium Niobate and Bismuth Ferrite which help create sustainability in piezoelectric tech. Piezo crystalline materials produce small amounts of electricity when a force (for example students' activities on walkways) is applied, this changes the shapes of the crystals in some way to generate electric energy as shown in Figure 1.

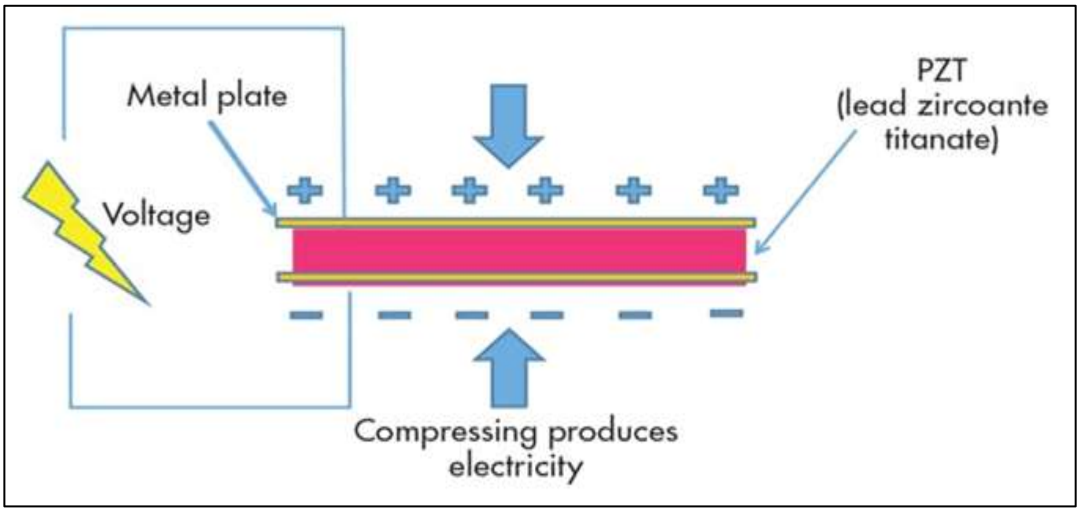

Figure 1: The piezoelectric effect occurrence during compression of a piezoelectric material

- **Mode of Operation**

Piezoelectric materials operate through the direct piezoelectric effects and the reverse effects as well. The material reacts to squeezing and bending by making an electric current, making it useful for both sensors and energy harvesters. Alternatively, these materials do not conduct, but still respond to an electric field, making it possible for them to precisely change shape in actuators and motion sensors. When small amounts of pressure are applied to the crystal structures, a small voltage is produced from the charge created by the moving electrons as can be seen in Figure 2. In this way, the piezoelectric effect acts like a miniature battery as it produces electricity.

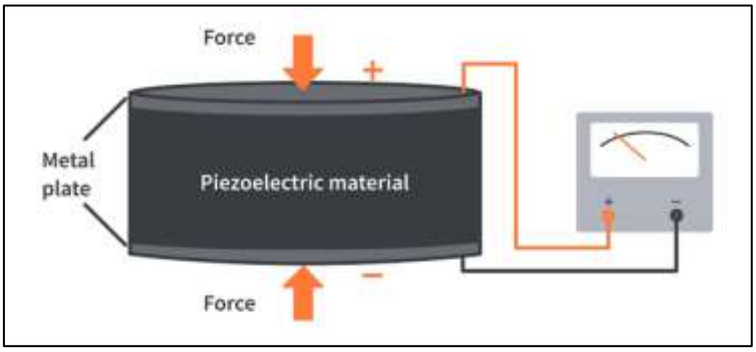

Figure 2: Monitoring Piezoelectric effect through voltmeter

- **Area of Application**

Piezoelectric materials are used widely in areas such as health monitoring, sonar equipment and the generation of solar-power. Because they can deal with rough conditions, use mechanical energy efficiently and last well, they are best suited for remote sensors, wearables and parts of smart infrastructure. Television at the relaxation point and phone chargers can be powered using this technology. However, the output voltage obtained from a single piezoelectric crystal is in millivolts range, which is different for different types of crystals. Nonetheless, this voltage can be cascaded to power a backup battery and subsequently power various appliances. They help a lot with conservation by supporting the growth of sustainable technology.

2.2 Review of Related works

The concept of utilizing piezoelectric materials for energy harvesting has gained significant traction over the past few years. Piezoelectric materials have the unique ability to convert mechanical energy into electrical energy, making them highly suitable for applications in energy harvesting. This technology is particularly promising for sustainable energy solutions in urban infrastructure, such as automatic lighting systems.

Piezoelectric energy harvesting has been explored in various contexts, from footstep energy capture to vehicular motion on roads. The advancements in piezoelectric materials, including both natural and synthetic options like lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF), have led to significant improvements in energy conversion efficiency. Research has also delved into the development of flexible piezoelectric systems, enhancing their applicability in diverse environments. The integration of piezoelectric systems with energy storage devices and automatic controls presents a comprehensive approach to creating sustainable and efficient lighting solutions. By harnessing energy from mechanical vibrations and storing it for later use, these systems can significantly reduce reliance on traditional power sources and lower overall energy consumption. In this literature review, we will explore various studies and advancements in the field of piezoelectric energy harvesting, focusing on their applications, efficiency, and integration with automatic systems. The reviewed papers will provide insights into the current state of technology and highlight the potential for future developments in creating sustainable urban lighting solutions.

In recent years, industrial and academic research units have focused their attention on harvesting energy from vibrations using piezoelectric material [3]. Cymbal transducer has been found as a promising structure for piezoelectric energy harvesting under such a high force vibration. The use of piezoelectric materials to generate electrical energy has long been a subject of research. These efforts have provided the initial research guidelines and have brought light to the problems and limitations of implementing the piezoelectric device. The work of [4]. proved the piezoelectricity effect after realizing that when pressure was subjected to quartz or even some certain crystals, electrical charge is generated in that particular material and called such occurrence piezoelectric effect. The work of [5], later verified that when an electric field was applied onto crystal leads, malformation or disorder to the crystal lead occurred, and such is referred to as the inverse piezoelectric effect. The work of [6], states that piezo means to "squeeze'' or "press" and the electric in Greek means "amber" that is, a source of electrical charge. Piezoelectricity is applicable to many electronic devices such as voice-recognition software, or Siri on smartphones. The microphone also uses piezoelectricity. Piezo crystal turns the sound energy in one's voice, and changes it into electrical signals for computer or phone to interpret.

Piezoelectricity can be applied in many ways not limited to: sensing change in pressure, force, and temperature [7]. Generating electricity by converting motion into energy, producing ultrasonic sounds, controlling acoustics in speakers, and even generating electrical signals. The piezoelectric effect has is often useful in electronics such as smartphones, laptops, sensors, LEDs, and more that we use daily. In addition, the electronic toothbrush, uses piezoelectricity to make physical vibrations that causes the toothbrush to vibrate and makes it easier to clean one's teeth. Also, for the microphone in a smartphone, it translates the sound from one's voice into electronic signals that can be read by an embedded processor to interact with certain apps and functions. A comparison of piezoelectric energy harvesting devices for recharging batteries was carried out in the work of [8]. In their study, three types of piezoelectric devices were investigated and experimentally tested to determine each of their abilities to transform ambient vibration into electrical energy and their capability to recharge a discharged battery. The three types of piezoelectric devices tested are; the commonly used monolithic piezo ceramic materials, lead-zirconate-titanate (PZT), the bimorph Quick Pack (QP) actuator and Macro Fiber Composite (MFC). Their results show that the Quick Pack and the monolithic piezo ceramic material PZT were capable of recharging the batteries in question. However, the PZT was shown to be more effective in the random vibration environment that is usually encountered when dealing with ambient vibrations.

Design of a prototyping roadway energy harvesting with piezoelectric crystal was presented in the work of [9] . Their paper presented a design that engages in educational activities to enhance learning in green energy manufacturing, including construction of piezoelectric energy collector system and laboratory experiments in the efficient energy harvesting of the system. Their findings also provided students with important knowledge about green energy design. A study by [10] worked on systematic review of energy harvesting from roadways by using piezoelectric materials technology. They investigated the process of harvesting energy from roadways starting from the used piezoelectric materials, harvesters and the conditions of the roadways. Many papers were evaluated and analyzed to study the current progress in the area including of the efficiency and feasibility of existent work. Their findings show that Lead Zirconate Titanate (PZT) is considered as the most efficient material due to its unique features according to many references and real or practical applications. Also, various factors such as geometry, thickness and structure affect the output of the piezoelectric process.

A study in [11] worked on piezoelectric materials for energy harvesting. In this paper various renewable sources of energy harvesting including solar, wind, wave and water flow, thermal, and vibration energy were reviewed. It also noted that piezoelectric materials used in energy harvesting devices are polycrystalline in nature due to their cost-effectiveness. On the other hand, single crystals exhibit a high piezo-electric response in certain crystallographic orientations resulting in enhanced energy output. However, the synthesis of large-size and high-quality single crystals has been quite challenging and expensive. The work of [12] designed an Automated Assessment of Balance, Fall and Step Response Using Piezoelectric Pressure Mats is an automated assessment system developed for assessing balance, fall, and step response. This system employs piezoelectric pressure mats to record and analyze human motion. Data from the pressure mats is then sent to a computer for analysis.

A system in which the operation of their technology relies on the Piezoelectric effect which occurs when an electrical potential is created across two parallel plates when one of the plates is mechanically deformed or compressed was designed in the work of [13]. When a foot is placed on the mat, pressure is applied on the PZT material, causing a deformation which induces a voltage across the plates. The voltage generated is then rectified and the electrical energy is used to power the smart device or charge a battery. The limitation of Advanced Structural Piezoelectricity Technology is that it requires PZT materials which have a high piezoelectric coefficient. The study by [14] examined how piezoelectric transducers can be used in low-power settings to generate electricity. It stresses the significance of power generation from ambient energy and the function of piezoelectric power in doing so. The study in [15] focused on the energy conversion and management that occurs in a hybrid harvester while operating under harmonic excitation. A prototype for analysing the energy potential of water flow in a pipe using micro turbines is also discussed, along with its construction. The authors [16] delved into the significance of renewable energy sources in solving environmental issues. In order to achieve sustainable development and lower greenhouse gas emissions, their work highlights the significance of renewable energy sources.

From the aforementioned review, it can be seen that the utilization of piezoelectric material to harvest energy from diffident purposes have gain wide attention in recent years, However, some major flaws still exist in the current state of piezoelectric floor mat energy harvesting systems, some of which are power limitations, where outputs (e.g., 134.2 µW [20]) are not sufficient for larger-scale applications [17], material challenges, where PZT toxicity and reduced effectiveness in PVDF require alternatives [18], [19], scalability challenges, where traffic variation and design complexities limit installation [20], and non-specificity, where comprehensive reviews do not encompass floor mat centrality, and older models may be outdated. These flaws necessitate targeted, sustainable designs for the academic environment. Therefore, this study aim to design, develop and implement energy harvesting techniques using piezoelectric device for powering electronics equipment in the relaxation Centre at the entrance of administrative block of School of Engineering and Engineering Technology Federal University of Technology, Minna, Nigeria

3. METHODOLOGY

This section presents the description of the study area, as well as the proposed system design and implementation. The system design is comprised of the various modules that form the working operation of project, and the system implementation shows the process employed to the achieve the fabrication. In addition, the various components used as well as the circuit diagram and the flow chart are presented.

3.1 Description of Study Area

The building proposed for the piezoelectric power generation study in this study is the School of Engineering and Engineering Technology Administrative building, Federal University of Technology, Minna Nigeria. The building is located in the centre of the active areas of the Gidan Kwano Campus. The building comprises of three stories, equal to a total of 16,000 m^2 in gross floor area with capacity of 500 seats available for students and 150 working staff.

The ground level of the building, holds the entrance, lobby meeting area- which has seats for watching television and charging o mobile phones for students, a cafeteria providing food and drinks for both students and staff, reading /lecture classes RM103, RM104, RM107 and RM108, there are also 2 male toilets and 2 female toilets, a store and 3 staff offices as shown in Figure 3.

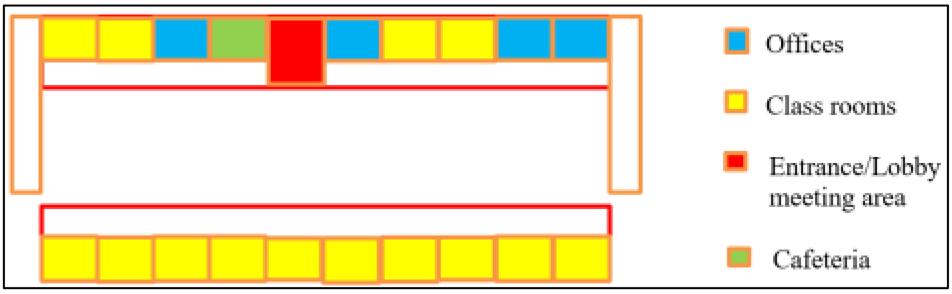

Figure 3: Layout of SEET Administrative Block

With these features, the entrance/lobby meeting area becomes a hub not only for the students, but also staff members in the school. It makes the area the busiest spot on the building, making the entrance to the building one of the target areas for deploying the piezoelectric tiles. In order to facilitate administrative work and student learning, the school administrative building opens seven (7) days a week during the year. The actual operating days of the building throughout the year, according to preliminary study is 224 days. The entrance and classrooms are never closed, even though the other offices and cafeteria are closed on Saturdays and Sundays.

3.2 Description of block diagram and system operations

The device is composed of two main components, the mat itself, which is made of a flexible, yet durable, piezoelectric material, and an electronic sensing device which detects and records the force and direction of the foot pressure exerted on the mat. The piezoelectric material in the Piezoelectric Foot Mat (PEEMat_Energy) produces electrical signals in response to the physical stress it experiences when it is compressed. The sensing device contains piezoelectric strain gauges that detect these electrical signals, which are then converted to physical force measurements by the built-in electronics. The resulting data is displayed on the PEEMat_Energy' s user interface. When the PEEMat_Energy is placed under the floor of the study location, it will accurately measure the force and direction of each step. The signal is collected at intervals during the student movements and passed through a rectified and filtered circuit to output 5V DC which can be further used to charge mobile devices and batteries of the given specification. The block diagram of the system is presented in Figure 4.

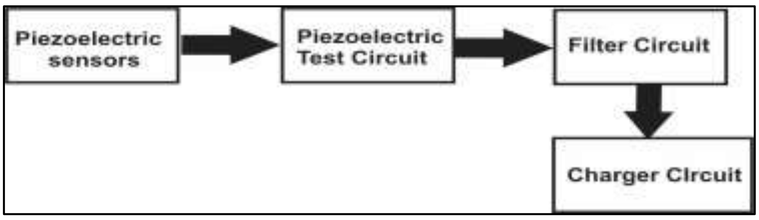

Figure 4: Block diagram of the system

3.3 Simulation Circuit Diagram

Schematic shown in figure 5 indicates 40 27mm PZT transducers in 4 strings of 10 wired in series to produce AC (5 – 20V peak per string, approximately 20 – 80V total) under 500N footsteps at 1–2 Hz. AC is fed to a 2W02G full-wave rectifier to provide approximately 18 – 75V DC after 2V drop. A 2F, 5.5V super capacitor buffers the DC and smooths input to the ND0603PC booster amplifier. ND0603PC (1 – 6V input, 0.26A) increases the voltage to approximately 3.7 – 5.5V (at 80 – 90% efficiency). The second 2F, 5.5V super capacitor filters the output, recharging two 3.7V, 100 – 500mAh LiPo batteries in parallel via a 1N4007 diode to prevent reverse current. No additional controllers are utilized, utilizing low piezo current (μA–mA) for safe charging.

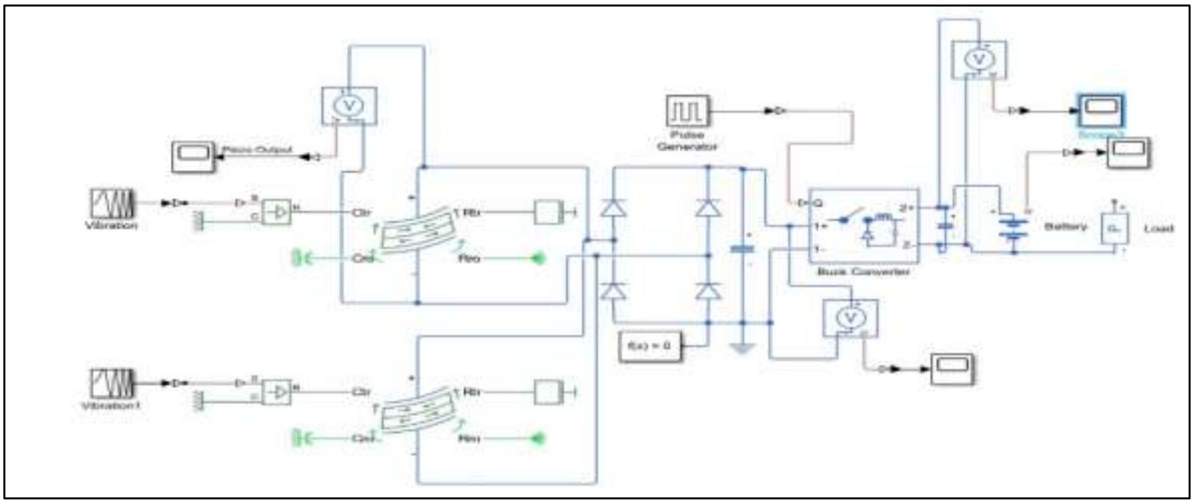

Figure 5: Circuit Schematic

3.4 System Flow Chart

The system flowchart shows the operation of the system. The system receives the signal of footsteps and if the person left stepping on the PEEMat, the vibrations produced will be converted to AC voltage, else the system waits for the person leaves the PEEMat. The AC voltage is further converted into DC voltage through rectification process the realized charge is stored in the battery. If there's load, the system will charge the load else, the system comes to an end. The system's flowchart is shown in Figure 6.

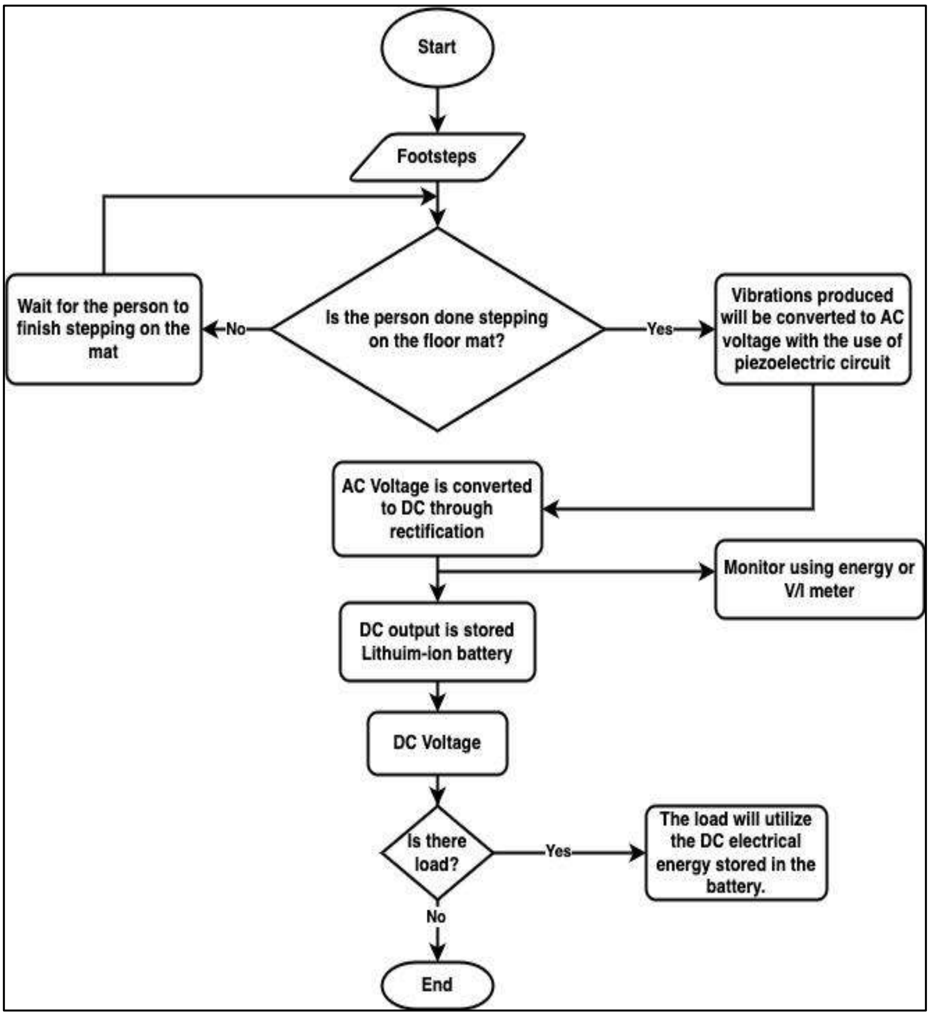

Figure 6: System flow diagram

3.5 Mathematical Relations

The equations used in the design of the Piezoelectricity foot mat are as follows:

Maximum Output Power P;

$$P = \frac{V^2}{R} = I^2R \tag{1}$$

Average Power

$$P_{avg} = V_{RMS} I_{RMS} = \frac{V_{Peak}}{\sqrt{2}} \frac{I_{Peak}}{\sqrt{2}} = \frac{V_{peak} I_{Peak}}{2} \tag{2}$$

Therefore;

$$P_{avg} = \frac{1}{T_{pulse}} \int_{t1}^{t2} \frac{V(t)^2}{R} \, dt = \frac{1}{T_{pulse}} \int_{t1}^{t2} I(t)^2 \, Rdt \tag{3}$$

Energy generated, $E = \frac{1}{2} CV^2$ (4)

This inverter is a single-phase full bridge inverter that converts DC to AC. It provides AC to isolated AC loads. The output of the full bridge inverter will connect to an LC filter which is used to limit the rate rise of inverter output voltage.

Equation (5) and (6) is used to derive capacitance and inductance values respectively.

$$L = \frac{V_{dc}}{4 * f_{sw} * \Delta i_{ppmax}} \tag{5}$$

$$C = \left(\frac{10}{2 f_{sw}}\right)^2 * \frac{1}{L} \tag{6}$$

Where C is the filter capacitances value

L_l is the filter inductance value

F_{sw} is the switching frequency of the filter

ΔI_{ppmax} is ripple current of the filter

V_{dc} is bus voltage

Modulation index was set to 0.85

4. RESULTS AND DISCUSSION

The simulation conducted using MATLAB/Simulink, mimic the system with 500N footsteps between 1 – 2 Hz. Each set of transducers yields 5 – 20V AC, for a total of ≈ 20 – 80V combined, which is rectified to approximately 18 – 75V DC. The first super capacitor charges about 5–6V, feeding the ND0603PC, yielding approximately 3.7 – 5.5V. The second 2F, 5.5V super capacitor reaches 5.5V in about 10 – 30s. The two 3.7V LiPo batteries, starting at 2.88V, gain approximately 5 – 20mAh over 10 minutes. Power output averages about 400 – 600µW/step exceeding the benchmark of 134.2 µW/step [20], and meeting the target of >400 µW/step. The prototype with plywood substrate is used due cheapness (80,000 – 100,000 per unit) and can be scaled up. Testing was done at 1,000 steps to evaluate voltage, power, efficiency of storage, and lifespan.

4.1 Scope output of piezoelectric Transducer under stress

The scope output image in Figure 7 displays the response of a piezoelectric transducer to mechanical pressure, showing a fast, densely packed wave that stabilizes in amplitude as time goes on. To begin with, the result shows a sudden increase in output as the material in the piezoelectric element changes with the applied force. When a material is exposed to shocks, compression or vibrations, that is called dynamic mechanical loading. As it moves from left to right, the waveform stays at a constant level of oscillation which demonstrates regular energy transfer into electricity. The yellow wave in a blue background on the plot shows that the piezoelectric element is responding to an oscillating or resonant force which is often sinusoidal in harvesting energy from vibrations. It appears from the steady amplitude and frequency in the later part that the material is optimizing its energy conversion at its resonant frequency. In smart structures designed to harvest vibration energy, piezoelectric devices produce electricity from repeated, stable forces.

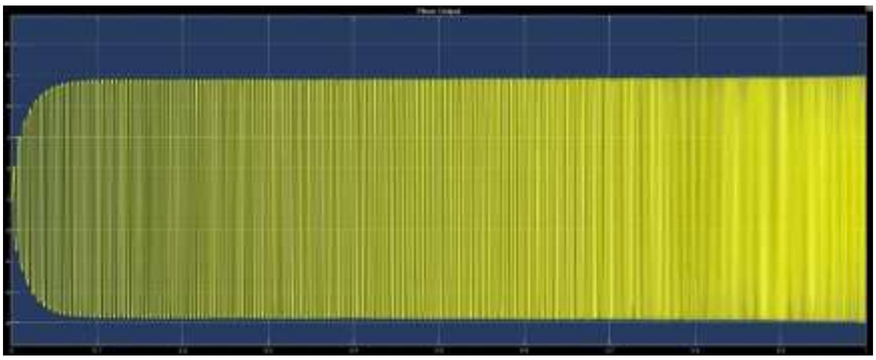

Figure 7: Scope output of piezoelectric Transducer under stress

4.2 Scope output of the bridge rectifier

The output waveform in Figure 8 displays the voltage generated by a bridge rectifier attached to a piezoelectric floor mat for sustainable energy harvesting. The early waveform demonstrates a rapid change in voltage, typical of the transient response at the instant the piezoelectric mat is pushed by the finger. This is followed by a stable waveform with less oscillation, demonstrating conversion of the AC produced by the piezoelectric element into DC current. The obvious ripple around the middle portion indicates that the rounding up is incomplete, a trait usually found in rectifier circuits lacking or having little filtering. The vibrations caused by footsteps or similar pressures cause the output quantity of DC voltage to increase continuously. Lowering noise and smoothing out the shape on the right-hand side indicate that the system has stabilized and effectively transformed energy to direct current. With this outcome, the bridge rectifier converts the piezoelectric AC to the useful DC power needed by low-power devices and storage systems in sustainable energy systems like smart floors and urban energy-harvesting technology.

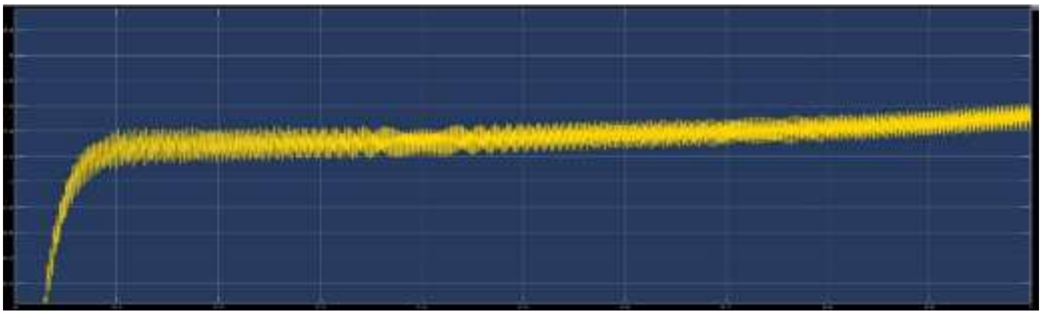

Figure 8: Scope output of the bridge rectifier

4.3 Scope output of the boost converter

From Figure 9, the voltage on the boost converter keeps increasing, then it becomes steady at a step-up level due to proper regulation from a low input voltage. It was observed also that the converter rapidly reaches its target output before settling into a flat, controlled and nearly ripple-free curve throughout the test. This behavior proves that the converter works well and reliably in raising the voltage from the piezoelectric system to a useful level to drive downstream devices or for storing power in energy-harvesting cases.

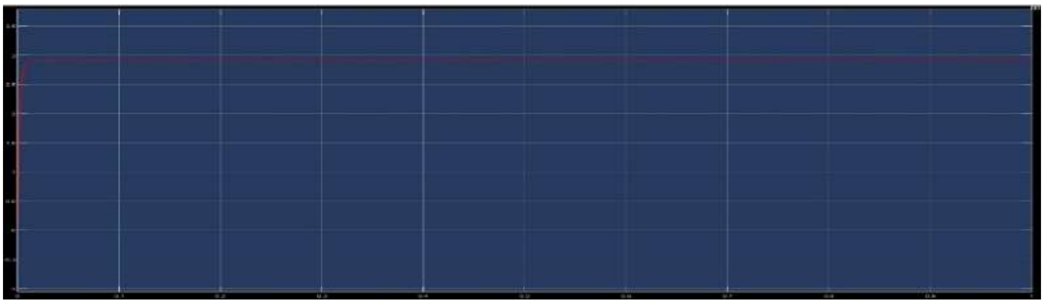

Figure 9: Scope output of the boost converter

4.4 Scope Output of the battery with and without Load

Figure 10 demonstrates that the voltage of the battery remains fairly the same without a load on it. Which reflects what the battery's voltage is when not connected to a load. No red line appears on the graph, showing the battery doesn't use charge and keeps its chemicals at a constant level. Because the battery isn't giving up energy, the voltage decreases or hardly changes when it is loaded. while the scope output of the battery with load in Figure 11 shows that the battery starts to release current as time goes on when loaded which results in a reduced voltage. The battery gives off less and less energy as time goes on, showing in the drop of the red graph and terminal voltage.

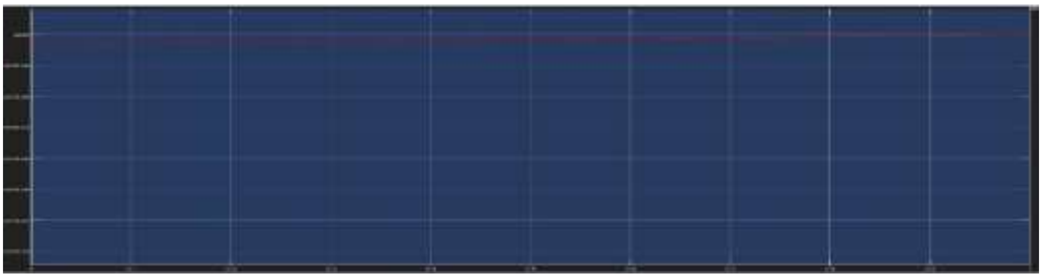

Figure 10: Scope output of battery without load

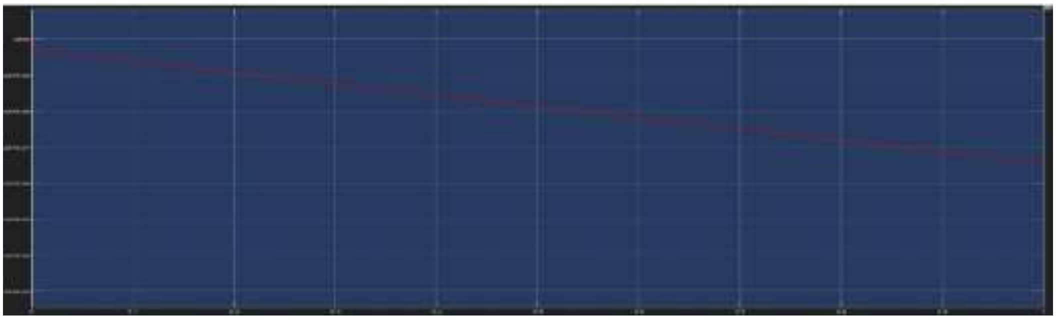

Figure 11: Scope output of battery with load

5. CONCLUSION

The study demonstrates that piezoelectric floor mat systems present a promising and viable solution for sustainable energy harvesting in high-traffic environments such as educational institutions and public facilities. The proposed design, which incorporates 40 piezo transducers, rectification, filtering, energy storage components, and an amplification circuit, has been validated through both simulations and preliminary experimental assessments. Results indicate that the system can generate sufficient electrical energy from mechanical stimuli, such as footsteps, to charge batteries and power low-energy devices, thereby contributing to off-grid and renewable energy initiatives.

The simulated power out was between about 400 and 600 µW for each step, while the rectified voltage was over 20V AC and operational DC voltage was between 18V and 75V. Super capacitors and LiPo batteries were added to the energy storage and by doing so, we had a good power source for devices with low power demand. Because the system is scalable and easy to adapt, it can work in many crowded areas and help reduce dependence on traditional energy. Nevertheless, finding better ways to convert energy, expand production and choose sustainable materials are still difficult. Future work needs to be done by using these materials in real environments, finding more environmentally friendly options for piezoelectric materials and improving the design of the circuits to obtain better results. In general, these mats have a bright future helping sustainably, economically and supporting nature's wellbeing.

Acknowledgement

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