Asian Journal of Research and Reviews in Physics

3(4): 53-64, 2020; Article no.AJR2P.63403
ISSN: 2582-5992

Effect of Time Factor on the Battery Voltage State of Charge from Foot Beats Piezoelectric System

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Authors' contributions

This work was carried out in collaboration among all authors. Authors GCN and UVO conceptualised and designed the study. Authors GCN, PUO and UVO managed the literature searches, fabricated the experimental platform, performed the experiment. Author PUO managed the analyses of the study. Authors UVO and NAO supervised the entire stages of the study including the experiment and verification of results. Authors GCN and PUO wrote the initial draft. All authors reviewed and edited the draft, read and approved the final manuscript.

Article Information

DOI: 10.9734/AJR2P/2020/v3i430129
Editor(s):
(1) Dr. Khalil Kassmi, Mohamed Premier University, Morocco.
Reviewers:
(1) Mohuya Chakraborty, Institute of Engineering & Management, India.
(2) Ming Chun Hsieh, Kun Shan University, Taiwan.
Complete Peer review History: http://www.sdiarticle4.com/review-history/63403

Original Research Article

Received 28 September 2020
Accepted 03 December 2020
Published 21 December 2020

ABSTRACT

Aim: The study examined the effect of time on amount of voltage generated in a foot beat electricity generating system stored in a battery.
Study Design: A system made of piezoelectric materials was designed such that the foot beats of dancers on a platform would cause a mechanical deformation that would lead to conversion of mechanical energy due to pressure from the foot beats to electrical energy; and can be stored in a rechargeable lead acid battery for future use.
Place and Duration of Study: Awka Anambra State, Nigeria, between November 2018 and April 2020.
Methodology: A sheet of plywood measuring 300 mm x 300 mm x 3 mm thick was placed on a hard wooden board of 300 mm x 300 mm x 25 mm thick where twelve piezoelectric sensors were

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connected in series with foam spring inserted as separators and to aid in returning after deformation. As the dancers step on the platform, multimeter was used to take the voltage and current readings, while Lead acid rechargeable battery could be connected at the output point to store energy generated in the system and or Light Emitting Diodes (LED) and Universal Serial Bus (USB) outputs. A stop clock was also used to take the time.

Results: The study revealed that it would require 901 seconds for a 50kg dancer to increase a unit voltage state of charge in a battery. It also found that it would require 749 seconds for a 60 kg dancer; and 595 seconds for an 80kg dancer respectively to increase the same 1-unit voltage state of charge in a battery. The study showed that the voltage in the battery would continue to increase until the battery is fully charged at which point it is expected that there would no longer be any increase in charge in the battery irrespective of increase in the number of foot beats or time.

Conclusion: The result implies that the charge in battery caused by pressure from the foot beats is subject to the maximum voltage capacity of the battery in the system. Likewise, the amount of time and number of foot beats required to add a unit voltage state of charge in a battery in the system is subject to the applied pressure from the foot beats. In view of this, the study craves for popularisation of this technology through large scale research supported by government, corporate organisations or international organisations and institutions that will support new products development in the building and construction industry as it is the case in India and other developed countries.

Keywords: Battery; foot beats; piezoelectric system; voltage; state of charge; time.

1. INTRODUCTION

More than 12 decades after electricity was introduced in Lagos, Nigeria, there has not been any substantial development and improvement in the electricity provision in Nigeria; rather the challenges facing electricity in Nigeria have been deepened [1,2]. The Advisory Power Team classified the challenges facing the Nigeria power value chain into generation, primary energy gas, transmission and distribution [3].

Similarly, for more than 20 years prior to the return of democracy in Nigeria, the power sector did not witness any substantial investment in infrastructural development. However, the past 2 decades have witnessed a lot of reforms and huge investment in the power sector [1,2,4-6], yet not much have been achieved in terms of improvement in electricity provision in the country. Besides the declining level of fossil fuels in the country, over-reliance on conventional sources of energy for provision of electricity in Nigeria has come with a lot of environmental, economic and social consequences [7,8].

To overcome the problem of unavailability of electricity and extensive power interruptions, there should be a shift to alternative energy sources as the viable options [9-11], because they are limitless and renewable. Secondly, the global issue of greenhouse gas that gives rise to global warming is on the rise. So alternative energy that is renewable is of great essence because, they cannot run out as it is the case of fossils fuels which are the major sources of energy in Nigeria [12,13].

Although search for alternative sources of energy with minimal consequences has led to the development of different methods and sources of alternative energy technologies such as solar, tidal, wind, biomass, hydro, and geothermal; the problem of electricity provision in Nigeria is still unabated. The application and utilisation of these technologies have been meted with severe challenges [13-17]. Most of these methods are not environmentally, economically and socially sustainable [18-22], thus, the need for a more sustainable method of generating electricity especially for common people and small scale electricity consumers and business outfits.

Interestingly, human body possesses a lot of potential energy that can be maximised when the body is in motion [23-26]. However, most energy are concentrated at the lower limb especially at the foot and heel region [23-26]. Unfortunately, the energy is expended and wasted as we walk, run or dance while it could be harvested, converted and optimised into useful form with minimal cost and effort. But since energy is inconstant and furthermost energy has vanished in nature, the thought of green-energy is to renovate numerous energies into electrical energy [27]. Thus, the ability to develop a system through which human foot beats generate electricity over time as an alternative to conventional source of energy for use at least for small energy consuming appliances and small scale business ventures is a pointer to a healthy economy in Nigeria.

The fact that Lead Acid Rechargeable Battery is connected in a piezoelectric setup and what happens to the battery in the course of energy generation in the system is a source of interest. To this end, this study evaluates the effect of time and number of foot beats on amount of voltage state of charge in a battery connected to a piezoelectric system.

This paper was organised into five sections. Section one is the introduction which gives the general background of the study, the research problem(s) and the objectives of the study. Section two deals with the theoretical and literature review where the theoretical equations underlying the study was discussed in addition to the empirical reviews. Section three deals with the materials and method including the working principles and experimental setup. Section four presented and discussed the results of the study, whereas section five presented the conclusion and recommendation based on the results.

2. THEORETICAL AND LITERATURE REVIEW

2.1 Theoretical Equation

Theoretically, energy produced by the piezoelectric sensors is given in Equation 1 as;

$$\mathrm{E} = \mathrm{P} \times \mathrm{t} \tag{1}$$

Where, P = Power measured in Watts and t = Time taken.

Furthermore, piezoelectric materials are known to generate voltage across their surface whenever they are subjected to mechanical stress and the generated voltage is stored in a capacitor such that the relationship between the stored charge and voltage is shown as in Equation 2;

$$\mathrm{Q} = \mathrm{C} \times \mathrm{V} \tag{2}$$

Where, Q = Charge measured in coulombs, C = Capacitance measured in Farads, V = Voltage across the capacitor measured in Volts. The energy produced by the piezoelectric sensors follows directly from Equation 2, and given as in Equation 3;

$$\mathrm{E} = \tfrac{1}{2}\mathrm{Q} \times \mathrm{V} = \tfrac{1}{2}\mathrm{C} \times \mathrm{V}^2 \tag{3}$$

Where, E = Energy measured in Joules. The voltage generated by the piezoelectric crystal is also given as in Equation 4;

$$\mathrm{V_g(t)} = \mathrm{d_{33}} \times \frac{\mathrm{f(t)}}{\mathrm{C_p}} \tag{4}$$

Where: (t) = pressure, d_{33} = the piezoelectric strain constant, Cp = piezoelectric crystal equivalent capacitance. But C_p is given as in Equation 5;

$$\mathrm{C_p} = \mathrm{k} \times \frac{\mathrm{A}}{\mathrm{h}} \tag{5}$$

Where k = dielectric constant.

After the polarisation of the piezoelectric crystal material, the piezoelectric sensors will produce deformation (i.e., when under pressure). Hence, the piezoelectric sensors on both sides of the conductive layer will produce charge and voltage. In this case, the piezoelectric sensors can be equivalent to a capacitor and a resistor in parallel; though the capacitance is very small but the parallel resistance value is very large. The pressure and the voltage generated by the piezoelectric crystal V(t) can be expressed as in Equation 6;

$$\mathrm{V_g(t)} = \frac{\mathrm{f(t)}}{\mathrm{A}} \times \frac{\mathrm{h}}{\mathrm{G_{33}}} \tag{6}$$

Where; (t) = pressure, A = Crystal surface area, h = Crystal thickness, G_{33}= Piezoelectric voltage constant, d_{33}= Piezoelectric strain constant, C_p= Piezoelectric crystal equivalent capacitance.

Since the weight of human body is fixed every time the force F is applied to the piezoelectric sensors, the generated voltage, V_g becomes

$$\mathrm{V_g} = \mathrm{AG_{33}} \tag{7}$$

Therefore, energy produced by the piezoelectric sensors then becomes

$$\mathrm{E_g(t)} = \frac{1}{2}\mathrm{C_P} \times \mathrm{V_g^2} \tag{8}$$

Equations 6 and 7 implies that the piezoelectric voltage is very high, while the piezoelectric equivalent capacitance is small and when the pressure is removed, the charge above the piezoelectric crystal will disappear. When the piezoelectric crystal is under force, it produces charges, and the voltage is high otherwise the voltage across the capacitor is low. The charges move to the storage capacitor and sets the voltage on the storage capacitor C_s as V_s. When the voltage across the capacitor C_s is the same as the voltage across the piezoelectric crystal C_p, then, the charge in motion stops such that, $V_p = V_s$, assuming the piezoelectric ceramic equivalent resistance is very large. This is in accordance with the law of conservation of charge as presented in Equation 9.

$$V_s = \frac{C_p x V_g}{C_s + C_p} = \frac{(f\frac{(t)}{A})hC_p}{(C_s + C_p)G_{33}} \quad (9)$$

2.2 Empirical Review

Recent studies have shown great interest in harvesting energy from human motion to replace conventional batteries for smart electronics [23-26,28-38]. According to Elahi et al. [24] human motion exhibits excellent potential to providing sustainable and clean energy for powering low-powered electronics, such as portable instruments and wearable devices. However, the application of piezoelectric system has been extended to achieving sustainable buildings [39,40], but not without challenges [41].

Based on the design of piezoelectric system, different factors that have influence on the amount of energy generated in the system have been identified. Izadgoshasb et al. [32] studied the effect of orientation of the cantilever beam with tip mass on the efficiency of the power generated in a piezoelectric system and found that by varying the orientation of the piezoelectric energy harvester (PEH), the efficiency of the energy harvester can be significantly increased. It further found that the maximum power is found to be achieved when the PEH is orientated at 70° with reference to a coordinate system attached to the leg when walking on a treadmill.

Riemer and Shapiro [26] revealed that a person weighing 80kg and walking at approximately 4km/h generates approximately 2W power from the heel strike. Similarly, Elhalwagy et al. [42] found that piezoelectric floors can generate many microwatts up to many watts per step, depending on space pedestrians' frequency and piezoelectric technology. An experimental study conducted by Kuang et al. [43] on a sandwiched piezoelectric transducer (SPT) with flex end-caps showed that an average power of 4.68mW was produced when the system was subjected to a 1 kN^2Hz sinusoidal force applied. A further application of the SPT as a footwear energy harvester was demonstrated by fitting the SPT into a boot and performing the tests on a treadmill, and the SPT generated an average power of 2.5mW at a walking speed of 4.8km h^{-1}.

Furthermore, while analysing the maximum energy that can be extracted from a piezoelectric harvester subject to pulsed excitation, with an interface circuit composed by a standard bridge rectifier, Cascetta et al. [44] showed that the optimal voltage of the DC load of the bridge rectifier is a fraction, comprised between 1/3 and ½, of the open-circuit voltage, depending on the piezoelectric losses and excitation time. For Ibhaze et al. [45], the amount of energy generated directly depends on the applied pressure while the voltage and current maximisation follows directly from the series-parallel connection of the transducers.

In the same vein, Ju and Ji [34] examined the indirect impact-based piezoelectric vibration energy harvester and found that the maximum power of 963.9μW and 11.9% power decrease after 489,600 cycles were obtained. However, the maximum peak-to-peak open circuit voltage of 42.2V and average power of 633.7μW were obtained at 3g acceleration at 17Hz. In their study, He et al. [46] investigated generated electrical voltage and output power in practical conditions under different strokes and step frequencies using piezoelectric elements. It was found that the maximum peak-to-peak voltage was 51.2V at a stroke of 5mm and a step frequency of 1.81Hz, while the corresponding output power for a single piezoelectric beam was 134.2μW.

An experimental study conducted by [28] using the finite element method to analyse the magnetic frequency-up conversion effect, generated voltage and transmission torque showed that the average power generation and normalised power density were 1.74 mW and 820.38 $\mu W/cm^3 \cdot Hz^2$, which are, respectively, more than 4 and 10 times that of previous works. According to this study, an embedded generator enables smart watches and wristbands to be self-powered. Zhou et al. [48] however, revealed that the average output power improves from approximately 1.5 mW to 11.8 mW when motion speed increases from 4 km/h to 8 km/h, but the maximum power density under human motion is 61.9lWg1, with a total weight of 190.7g.

On the other hand, several studies have focused on the methods of estimating the state of charge of a battery [49-53]; others studied the techniques of charging lead-acid battery [54-57]. Although Rakshana [56] highlighted different techniques of changing lead-acid batteries such as constant current charging, constant voltage charging methods and use of converters, the study proposed the use of Buck Boost converters because of their many advantages such as: charging multiple batteries simultaneously with the series-connected Buck Boost BPM; controlling the battery current by adjusting the duty ratio of the buck-boost converter; controlling the charge and discharge of each battery by adjusting the working ratio of the connected converter; and isolating fully charged batteries or damaged batteries without interrupting the charging process. However, one of the method of measuring the state of charge in a battery is the amount of voltage generated during the charging over time [49]. The measurement of the state of charge allows efficient management of the battery's power in addition to avoiding the overcharge, thus extending the life cycle of the battery [54].

Although current interests have focused on how to harvest the unused natural waste energy sources due to the rising power demand [47], Yang et al. [48] argue that it is not appropriate to compare different designs by one figure of merit due to the complexity in dynamics, structures, and electromechanical coupling of energy-harvesting systems. Besides, the system also comes with its challenges [41] in addition that certain parameters such as the state of charge, the lifetime of the battery, and the charging time must be taken into consideration when designing a charger of a battery [54]. Therefore, evaluating the import of time and foot beat beats on the amount of voltage state of charge in a battery connected to a piezoelectric system becomes pragmatic.

3. MATERIALS AND METHODS

The selection of materials, working principle and model prototyping are required in the design of foot beats piezoelectric system. The design, setup and material adopted in this study for experimental result are presented in this section. According to Ibhaze et al. [45], the amount of energy to be converted, the working principle of piezoelectric sensors, and the generation of energy are the requisite for prototyping a possible solution in the selection of the type of material used in a piezoelectric system. In this case, the piezoelectric generator is setup to generate electrical voltage which would be stored in the Lead acid rechargeable battery through the application of pressure from the foot beats of dancers in dance club centres using piezoelectric sensors.

3.1 Materials

This study used the following materials for experimentation: 300 mm x 300 mm x 25 mm thick wooden board, 3 mm thick plywood of the same dimension, 150 mm x 150 mm electric unit box, human weight of different kilogrammes, electric panel, foam spring, Lead Zirconate Titanate, (PZT-5) piezoelectric sensors, rectifier (diodes), capacitors, resistors, 6V4AH Lead acid rechargeable battery, multimeter, AC nipple neutraliser, current controllers (switches), electric strand wire, LED and USB output.

3.2 The Working Principle and Experimental Setup

A sheet of plywood was placed above the 12 piezoelectric sensors unit connected in series on a hard wooden board, because the power output from one piezo crystals were found to be very low. Between the plywood and hard board, a foam spring area unit was placed at the corners and nails area unit placed on the second board such as the sensors at the middle of board in 3 x 4 arrangement as shown in Fig. 1. Subsequently, the piezoelectric platform was prepared for stepping.

Usually, the output voltage from a single piezo-sensor was extremely low, therefore combination of 12 piezoelectric was used. Since the output of the piezoelectric material is not a regulated one, variable to linear voltage converter circuit rectifier was used. In this case, AC ripple neutraliser was the circuit used to reduce the ripples from the piezoelectric output. The AC ripple neutraliser consists of rectifier and ripple filter. AC ripples were filtered out using ripple filter and it was used to filter out any further variations in the output and then it can be passed through regulator in order to regulate, and it is constant until the load and mains voltage is kept constant.

Likewise, the output of the voltage regulator is given to the unidirectional current controller which allows flow of current in only one direction. In this system, diode was used as a unidirectional current controller whose main function was to allow the flow of current in only one direction while blocking current in the reverse direction. The piezoelectric sensors convert the pressure from the foot beats to electrical energy when pressed and store same in batteries that can be used in real time or at a later time to power the desired devices. A battery was connected to the system to store energy for future use. In this instance, a LED display was shown using this foot power. The block diagram of footsteps electricity generation is shown in Fig. 2. The block diagram represents a typical piezoelectric energy generating setup and it's shown in Fig. 2.

As the gadget was placed under the dancing floor, electricity was generated from the pressure from the foot beats of dancers. The voltage generated from the system was stored in the battery which could be used to power electrical appliances when the pressure was withdrawn. Multimeter was used to determine the amount of voltage generated in the system. As varying forces (foot beats) were applied on the Piezo material, different voltage readings corresponding to the force was displayed and recorded.

4. RESULTS AND DISCUSSION

4.1 Assumptions

1. The experiment was conducted in a club house where the dancers dance to the beating rhyme of a music.
2. The dancers dance at the same pace and frequency irrespective of the weight of the dancer.
3. A dancer made an average of 2 foot beats per second while dancing to the music rhyme.

As piezo sensors power generation varies with different foot beats and weights of persons, multimeter was connected across for measuring voltages and current. Thus, varying forces were applied on the Piezo material; different voltage readings corresponding to the force were displayed. For each voltage reading across the force sensor, various voltage and current readings of the Piezo material were recorded as presented in Table 1.

Fig. 1. The arrangement of piezo sensors and connections in the system

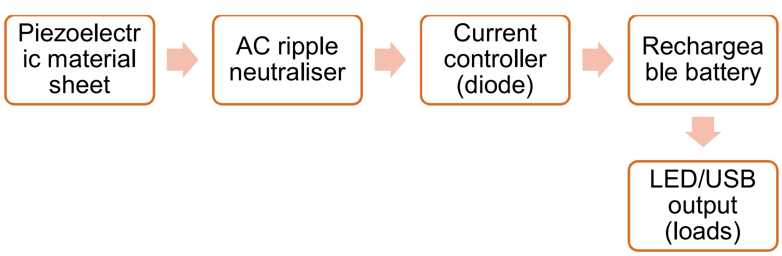

Fig. 2. Block diagram of footsteps electricity generation

Table 1 presented the voltage reading of each piezo sensor used in the system. It shows that an average of 0.555 millivolts 0.668 millivolts and 0.838 millivolts were generated per foot beat in the system from 50kg, 60kg and 80kg weight of dancers respectively. From the stated assumptions, a dancer irrespective of his weight made an average of 2 foot beats in 1 second while dancing. All things being equal, in 1 second, 1.11 millivolts, 1.336 millivolts and 1.676 millivolts were generated in the system from 50 kg, 60 kg and 80 kg weight of dancers respectively. However, it took a 50kg dancer 901 seconds (15 minutes 1 second) to increase 1-unit voltage in a battery in the system. Similarly, it took 60 kg and 80kg dancers 749 seconds and 595 seconds respectively to increase 1-unit voltage in a battery in the system. The experimental observation is presented in Table 2 for the instance case where a 6 Volts rechargeable battery was connected to store the voltage generated in the system.

Table 2 showed that the amount of voltage state of charge in battery will continue to increase as a result of increase in time until the battery is fully charged. Conversely, as the average weight of dancers increases, the amount of time required to increase a unit charge in the battery becomes lesser. This implies that there are greater pressures emanating from the increased weight of dancers. In this case, it took about 5406 seconds for an average weight of 50kg dancer to fully charge a 6 V battery used in this study. Likewise, an average time of 4494 seconds was expended by an average weight of 60kg dancer; and 3570 seconds by an average weight of 80kg dancer respectively to do the same. That is to say that it would take about 5406 seconds, 4494 seconds and 3570 seconds for a 50kg 60kg and 80kg dancer respectively charge a 6V battery 100% if other factors remain constant. The graphical representations of these phenomena are shown in Fig. 3.

Fig. 3 compares the amount of time required for a 6V battery used in this study to be fully charged using dancers with different weights. It shows that amount of time required will continue to increase until it gets to a point when the battery will be fully charged and the voltage will remain steady. However, as the weight increases there are lesser amount of time required to increase the same unit of voltage in the battery.

Table 1. Piezo sensor voltage output for different weight

Piezo sensor	Voltage (mV)		
	50 kg	60 kg	80 kg
1	0.520	0.680	0.820
2	0. 612	0. 650	0. 860
3	0. 560	0. 680	0. 840
4	0. 540	0. 645	0. 770
5	0.560	0.680	0.860
6	0. 600	0. 654	0. 840
7	0. 582	0. 650	0. 864
8	0. 546	0. 684	0. 804
9	0. 522	0. 684	0. 866
10	0. 510	0. 645	0. 850
11	0. 558	0. 680	0. 842
12	0. 552	0. 680	0. 840
Average	0.555	0.668	0.838

Table 2. Time and number of foot beat required to increase a unit voltage in battery for different weights

Voltage (V)	Time (s)		
	50 kg	60 kg	80 kg
1	901	749	595
2	1802	1498	1190
3	2802	2247	1785
4	3604	2996	2380
5	4505	3745	2975
6	5406	4494	3570

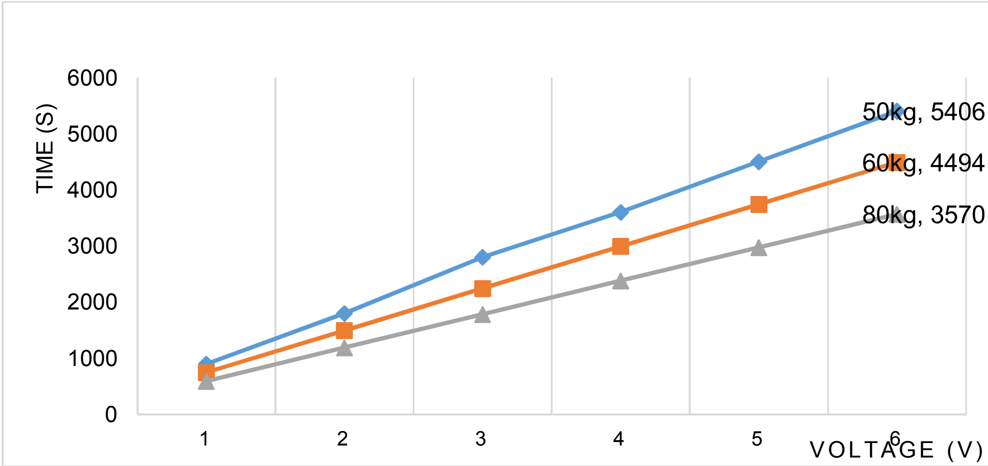

Fig. 3. Graphical comparison of time required to increase a unit voltage in a battery under different weights

Generally, the voltage will continue to increase with increase in time and number of foot beats or as a result of addition of dancers to the dancing floor until the battery is fully charged. At this point, it is expected that the voltage remains steady even when more pressure or foot beats are added or extension of time. This implies that though the number of foot beats and amount of time are determinants of the quantity of voltage received in a battery through charge, it is limited to the maximum voltage capacity of that battery.

Implicitly, this result shows that the amount of voltage state of charge in a battery is greatly dependent on the applied pressure since the amount of time required to add a unit voltage is also dependent on the weight of a dancer. Furthermore, the effect of time became irrelevant once the battery is charged to its full voltage capacity. It suggested that more pressure should be added to the system in order to reduce the time expended to reach a full voltage capacity in the battery. While [56] proposed the use of Buck Boost converters for lead-acid battery, [55] designed the circuit based on pulse for charging of lead-acid battery; whereas [57] developed a fuzzy logic for charging control of lead-acid battery in stand-alone solar photovoltaic system. In the current study, a new system of charging a lead-acid battery through foot beat electricity generation experimentation was developed. The study therefore, supported the views of [34,43,44,46]; and specifically shared the same view with Ibhaze et al. [45] who surmised that the amount of energy generated directly depends on the applied pressure while the voltage and current maximisation follows directly from the series-parallel connection of the transducers. This study equally supported [29] who noted that the development of wearable electronics and sensors is constrained by the limited capacity of their batteries. The study has therefore, made an appreciable input into developing a system of management of lead-acid battery. In an effort to developing a sustainable means of charging a battery, this study opens a new spectrum of research in the field of battery technology. In terms of charging time, charger's cost of a battery and reducing the damaging effects of lead on the environment, this system provided a suitable alternative.

5. CONCLUSION

As the problems of conventional sources of electricity persist, the search for a more sustainable alternative sources of energy continues to grow. Thus, this study has demonstrated that the wasteful energy in the human body that is lost through body movement and other human activities could be converted into a useful electrical energy and stored in a battery for future use using piezoelectric materials.

The study has shown that the amount of voltage generated and charge stored in a battery are dependent on the number of foot beats pressure applied in the system. It also showed that the length of time the system is subjected to the pressure is tactically immaterial. Invariably, the more the length of time the more the foot beats while every other thing remains constant. However, the overall quantity of voltage generated and charge stored in the battery are subject to the maximum voltage capacity of the battery regardless of the number of foot beats pressure received or time.

Since the voltage generated in this system can be stored as a charge in a battery for future use, this system is suitable only where minimal amount of electricity like club houses, markets, and worship centres, shopping malls, bus stations, parks, etc. is consumed. The system is also capable of powering small electrical appliances and electronic gadgets such as cell phones, radio stereo, television, fan, and even powering street lights on the highways through a system whereby vehicles run on the laid piezoelectric materials on the road.

Although there have been other alternative sources of energy, this system is relatively sustainable. It is economically viable, socially compatible and environmentally acceptable. Holistically, this system of electricity generation has potential for providing a viable option towards solving the electricity problems in Nigeria. In view of this, the study calls for popularisation of this research through large scale researches supported by government, corporate organisations or international organisations. There is also need for strong institutional support towards the course of this new technology innovation through new products development in the building and construction industry as it is the case in India and other developed countries.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/63403