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Renewable Energy Harvesting based on Lead Zirconate Titanate Crystal

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Abstract Contrast with the enormous demand on the insufficient capacity of the grid system, are the emerging techniques for off-grid power generation to lighten the demand on the grid. Measures to improve on uninterruptable power supply in developing and underdeveloped communities can be attested to by the total number of blackouts per time as ineffective measures are adopted to suffice the limitations. This work therefore proposes an efficient off-grid solution for energy generation using Lead Zirconate Titanate Crystal PZT - 5H for renewable energy harvesting for low voltage energy consumption. The adopted method is sensor-based whereby a sensor is used to trigger the switching of the energy harvesting setup, allowing for more efficient consumption. The piezoelectric energy harvester model was able to energize the connected LED lamps and can also be used to power up alternative energy efficient devices.

Keywords: Piezoelectricity, lead zirconate titanate, harvester, energy, crystal

1. INTRODUCTION

Energy generation has been debatable for quite some time due to the increase in human population over the years, which has brought about higher consumption of energy from residential, commercial and industrial users. However, energy harvesting has brought about a feasible means of curbing this problem and as a result reducing greenhouse effect. In energy generation, energy harvesting is not a new term as it is done on different scale in order to generate electricity for different purposes [1]. It is the process of accumulating energy such as thermal, solar, ambient and sound energy stored for use as electrical energy. This green energy technique is designed to reduce the number of emissions into the ozone layer thereby resulting in better greenhouse effect [2] [3]. One of such technique is piezoelectricity energy harvesting.

Piezoelectricity is the adaptability of specific materials known as piezo, to generate electricity in form of AC voltage by applying mechanical stress in the form of vibration, heat, light, and sound [4]. In general, it is the ability to generate electricity by applying pressure which works on the basis of a transducer converting energy from one form to another.

Piezoelectric energy harvesting is the transformation of pressure or mechanical stress to electrical energy while storing the harvested energy in batteries or supercapacitors for use by other low energy consuming devices [5] [6]. Vibrations applied unto these transducers (piezoelectric crystals), causes a change in the transducer by displacing the crystals and producing electricity as a result [7]. This is a form of renewable energy, which makes it eco- friendly, as emissions to the environment are reduced considerably as investigated in earlier studies [8] [9].

This work looks into the practicability of acquiring energy from a technique capable of generating vibrations applied unto piezoelectric crystals, a member of the ceramic Lead Zirconate Titanate (PZT) family. The energy to be harvested is used to power energy efficient devices such as mobile phones and

LED's among others. The piezoelectric crystal used is a soft ceramic type capable of producing very high power output compared to other ceramics occurring at low and non-resonant frequencies [10] [11].

The significance of this work is to increase the efficiency of energy harvesting using piezoelectricity, to reduce the demand on the electrical grid, as a result be a substitute for powering up off grid appliances such as streetlights and billboards among others rather than the use of the grid, generators or other conventional sources.

II. RELATED WORK

With the rapid growth in population, energy generation, distribution and consumption has been an open research problem in developing countries, arising from the limited power supply to commercial, industrial and residential consumers. A solution to this problem is the adoption of renewable energy models, been investigated globally as means to reduction of hazardous emissions and actualization of greener technologies.

In [12], the authors investigated potential energy generation through green sources. Previously, devices using piezo electric energy were based on generic power generation i.e. from low-power consuming electrical devices, such as wristwatches and RFID based applications [13]. The process of generating voltage from piezo ceramic posed a significant stage in the piezoelectric harvesting process. The means of generating the vibrations was through the application of mechanical strain on the piezo ceramic by mounting on a cantilever beam and a shaker exciter. The shaker generates vibrations that excite the cantilever beam where the piezo ceramic is mounted, applying mechanical stress to produces electrical energy as a result [14]. From the results, piezo ceramic was able to generate 2V, and increased to 5V using the boost converter [15]. It was also able to achieve 16V or greater due to the LM 2733 IC used. With modification of the circuit with a change in the boost converter and the IC, more voltage could be generated. A comparison between a Nickel Cadmium battery and a Lithium- ion battery was conducted in [16]. The lithium polymer battery was used as the electrical energy storage device and was used for powering devices such as mobile phones and other portable electrical devices. In another investigation on piezoelectric energy harvesters (PEH), two energy-harvesting systems namely compression based system and cantilever type system were compared to get the best power output [17]. Their connections were both in series and parallel which showed considerable improvement in power output in both cases. The compression based system consisting of an array of piezo crystals outperformed the cantilever type since piezos were excited at a resonant frequency generated from the motion of vehicle tires [18]. The vibrations resulted in the generation of AC electricity from the piezo, rectified through the use of an AC-DC diode rectifier and regulated before storage [19] [20].

In another work, a process of energy harvesting where energy extraction is not possible due to low excitation level called cold start-up was proposed. The authors investigated means of increasing the voltage generated by piezoelectric materials based on the conversion of the readily available ambient kinetic energy into electrical energy [21]. A self-charging model was proposed by further investigating piezos with high charge constant [22]. An SSHI rectifier was used for rectification since it extracts at low excitation levels and serves as a booster in [23]. The generated energy was stored in capacitors, with the SSHI rectifier design having two-off chop capacitors in the system for energy storage.

Generation of power from human footsteps was presented in [24] [25]. Its adoption received wide acceptance in densely populated metropolis due to easy access of pressure and strain from human locomotion applied to piezoelectric materials [26]. Generation of electrical energy from piezoelectric materials [27], applied to charging low voltage electronic devices such as mobile phones, laptops, etc. using in-shoe solution and wireless transfer was conducted by [28] [29] [30]. Diverse piezoelectric materials had been investigated for higher output voltage based on crystal combination [31] [32] [33]. Polyvinylidene difluoride (PVDF) and Lead Zirconate Titanate (PZT) had been investigated with findings typifying the superiority of PZT crystals due to the high efficiency in converting mechanical strain to electrical power with a variety in PZT-4 and PZT-5A [34] [35] [36] [37]. While a couple of PZT ceramic family had been used in previous research undertaking, PZT-5H will be used in this work due to its stability superiority at ambient temperature.

III. METHODOLOGY

In order to model piezoelectric energy harvesting device, the selection of materials, working principle and model prototyping are requirements in model design. In selection of the type of material, amount of energy to be converted, the working principle of piezoelectric crystals, and how the energy is to be converted are requisite in prototyping a possible solution. The piezoelectric generator is built to harvest ambient energy i.e. vibrations from the surroundings using piezoelectric crystals. This crystal converts the vibrations applied to electrical energy and stores same in batteries that can be used in real time or at a later time to power the desired devices. According to [38], since the joints of human body are always in continuous motion, they are dosed with the possibilities of energy harvesting when the human body is taken as the mechanical input source. In the work of [39] [40], human body has the capacity to generate 2 to 20W from foot strike, 38W via hip movement, 36.4W from knee motion, about 66.8W through ankle movement, 2.2W via the motion of the shoulders, 20W and 2.1W from earths center of gravity and elbow motion respectively. The translation of diverse weights to piezo vibration for energy harvesting in relation to human body exertion is given by [38] as;

$$E = \Delta P_M x \eta_M x \eta_D \qquad 1.1$$

Where E is the generated electric energy, ΔP_M is the change in metabolic power, η_M is the muscle efficiency in relation to energy conversion per motion and η_D is the device efficiency. The block diagram representation typical of a piezoelectric energy harvesting setup is shown in Figure 1.

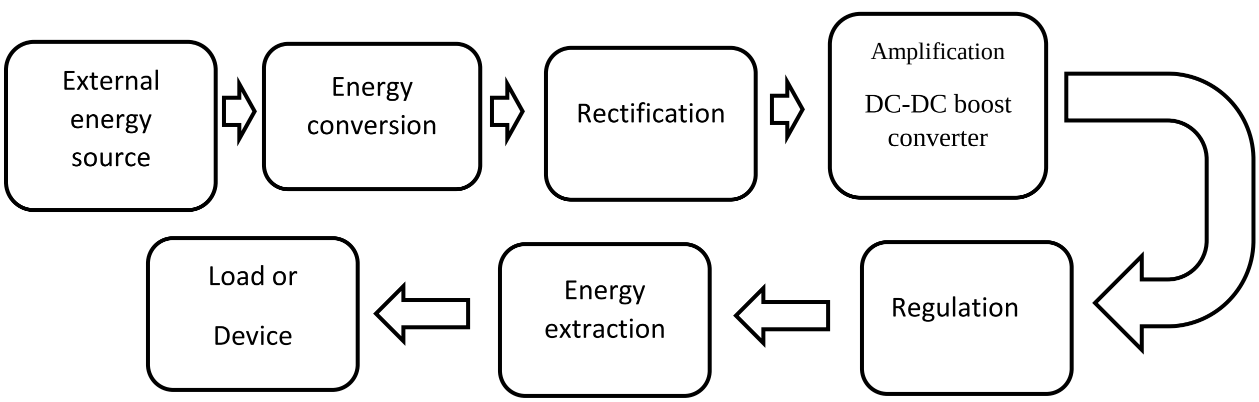

Figure 1: Block Diagram for the Realization of a Piezoelectric Energy Device

The connection diagram consists of six stages; External energy, Energy conversion, Rectification, Amplification, Voltage Regulation and Energy extraction module.

The External energy module is concerned with the source of energy that excites the piezoelectric material that converts the energy. The source of energy could be from human activities such as physical pressure exaction or some mechanized or industrial robotic operation of pressure exaction. Energy conversion deals with the transformation of mechanical energy in the form of vibrations to electrical energy using a piezoelectric transducer. The material used is a Lead Zirconate Titanate PZT - 5H transducer and the electrical energy generated is alternating current (ac) voltage. The rectification module converts the generated voltage to direct current (dc) voltage via synchronous rectifier. The amplification module increases the dc voltage by using a boost converter (dc-dc) [41]. The voltage regulation is used to remove ripples from the output dc voltage using a capacitor filter. The filtering gets rid of the ripple to generate a ripple free DC waveform. The energy extraction module is then used for the storage of the output voltage for future use.

According to [37], the energy produced by the piezoelectric disk is given by;

$$E = P\ x\ t \tag{1.2}$$

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

However, piezoelectric materials are known to generate voltage across their surface whenever they are subjected to mechanical stress. The generated voltage is stored in a capacitor such that the relationship between the stored charge and voltage holds [31].

$$Q = C\ x\ V \tag{1.3}$$

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 crystal follows directly from Eqn. (1.3) [19], given as;

$$E = \frac{1}{2} Q\ x\ V = \frac{1}{2} C\ x\ V^2 \tag{1.4}$$

Where, E = Energy measured in Joules

The voltage generated by the piezoelectric crystal is given by;

$$v_g(t) = d_{33}\ x \frac{f(t)}{C_p} \tag{1.5}$$

Where: $f(t)$=pressure

d_{33} = the piezoelectric strain constant

C_p = piezoelectric crystal equivalent capacitance

$$C_p = k\ x\ \frac{A}{h} \tag{1.6}$$

Where k = dielectric constant.

After the polarization of the piezoelectric crystal material, the piezoelectric crystal will produce deformation (i.e., when under pressure). Hence, the piezoelectric crystal on both sides of the conductive layer will produce charge and voltage. At this point, the piezoelectric crystal 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 $v_g(t)$ can be expressed as;

$$v_g(t) = \frac{f(t)}{A} \; x \; \frac{h}{G_{33}} \qquad 1.7$$

Where; $f(t)$= 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 crystal, the generated voltage, v_g becomes

$$v_g = AG_{33} \qquad 1.8$$

The energy produced by the piezoelectric crystal then becomes

$$E_g = \frac{1}{2} \; x \; C_p \; x \; v_g^2 \qquad 1.9$$

It is to be noted that the piezoelectric voltage is very high, while the piezoelectric equivalent capacitance is small. 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. Hence, according to the law of conservation of charge;

$$V_s = \frac{C_p \; x \; V_g}{C_s + C_p} = \frac{\left(\frac{f(t)}{A}\right)hC_p}{(C_s + C_p)G_{33}} \qquad 1.10$$

Setting ultimate energy on the storage capacitor as E_s, yields;

$$E_s = \frac{1}{2} C_s V_s^2 \qquad 1.11$$

By combining Eq. 1.10 and Eq. 1.11,

$$E_s = \frac{1}{2} C_s (\frac{C_p \; x \; V_g}{C_s + C_p})^2 \qquad 1.12$$

When $C_s >> C_p$, then Eq. 1.12 can be transformed into;

$$E_s = \frac{1}{2} \frac{C_s (C_p \; x \; V_g)^2}{C_s^2} \qquad 1.13$$

$$E_s = \frac{(C_p \; x \; V_g)^2}{2C_s} \qquad 1.14$$

The energy transfer efficiency is given as;

$$\eta = \frac{C_p}{C_s} \qquad 1.15$$

The capacitance is decided by the thickness of piezoelectric crystal and the piezoelectric parameters. When the capacitance is small, the transfer voltage is large, and the energy transfer efficiency is high. Hence, dc input voltage cannot be too high, so the value of the capacitance will not be too small. If the capacitance is too small, the discharge time will be too short. The energy harvesting prototype follows directly from the implementation of five transducers arranged in series-parallel combination of four layers, making a total of 20 connected transducers shown in Fig. 2. This connection technique is so implemented since series connection produces good voltages with low current value [33] while parallel connection gives good current at low voltage value. Further to this, parallel connection helps in reducing the total resistance value to the barest minimum. Hence, the series-parallel connection rectifies the problem were good voltages and currents are produced. Fig. 3 is the representation of the capacitor bank of the implemented model.

Figure 2: Energy Harvesting Prototype showing the arrangement of Piezo crystals

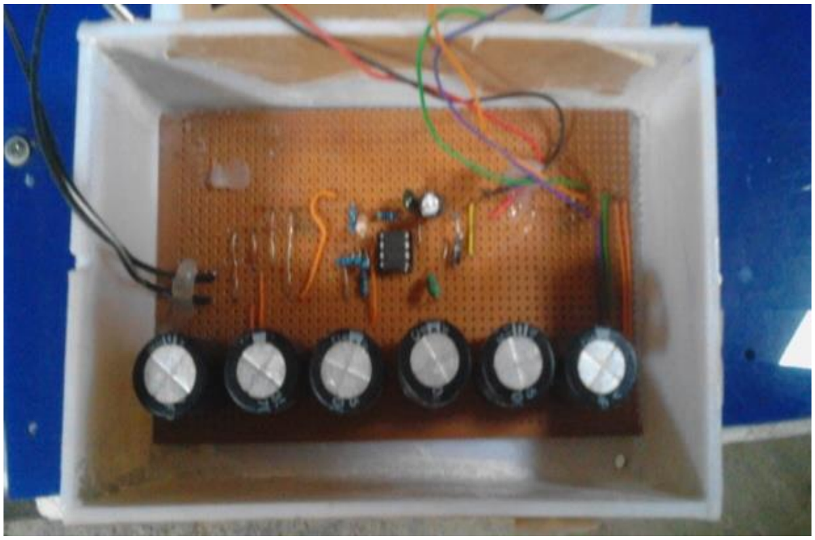

Figure 3: Energy harvesting prototype showing the capacitor bank

3. RESULTS AND DISCUSSION

Based on the experimental setup and testing, the specific parameters for model validation are as presented. The length of piezoelectric energy harvester, L = 19.05cm while the breadth of piezoelectric energy harvester, B = 29.718cm. So that, the surface area of the energy harvester is given by (19.05 × 29.718) = 566.1279 cm^2 (= 0.5661279 m^2). Different individuals with varying masses used to test the energy harvester gave different power readings at different weights. Averaging the impacted area over the entire surface area of the energy harvester, the length and breadth of the impacted surfaces are 19.05cm and 27.529cm respectively such that the area of impacted surface on the energy harvester becomes (19.05× 27.529) = 524.44cm^2 (= 0.52444m^2)

Note: The shoe size of the individuals (used to test the piezoelectric energy harvester) was taken as size 44 on the average.

The computation of the exerted force follows directly from

$$f_e = \begin{cases} m * a & \forall \quad 60kg \leq m \leq 90kg \\ o & Otherwise \end{cases} \qquad 1.16$$

Where f_e is the exerted force measured in Newton (N), m is the mass measured in kilogram (kg) and a is acceleration due to gravity measured in meters per square second (ms^{-2}).

The estimated pressure is given by:

$$p_e = \frac{f_e}{A} \qquad 1.17$$

Where p_e is the resulting pressure from the force exerted f_e. p_e is measured in Newton per square meter (N/m^2) and A is the area of the impacted surface of the energy harvester.

The estimated power was arrived at by taking the voltage and current readings using a multimeter when different weights were applied. Power computing therefore follows directly from;

$$P = VI \tag{1.18}$$

Where P is the measured power output of the energy harvester in Watt (W), V is the measured voltage value in Volt (V) and the measured current I in Ampere (A)

The resulting values from Eq. 1.16, 1.17 and 1.18 are presented in Table 2 for the basis of comparison.

Table 1: Theoretical values of voltage, current and power

S/N	Mass (Kg)	Force (N) g= 9.81 ms^{-1}	Pressure (N/m^2)	Voltage (V)	Current (A)	Power (W)
THEORETICAL VALUES				14.72	0.06	0.88

Table 2: Table of varying masses, forces, pressure, voltage, current, power experimental values

S/N	Mass (Kg)	Force (N) g= 9.81 ms^{-1}	Pressure (N/m^2)	Voltage (V)	Current (A)	Power (W)
1	60.00	588.66	1122.34	5.90	0.01	0.06
2	65.00	637.65	1215.86	8.40	0.02	0.17
3	70.00	686.79	1309.39	9.30	0.02	0.19
4	75.00	735.75	1406.74	12.50	0.02	0.25
5	80.00	784.89	1496.45	15.30	0.05	0.77
6	90.00	882.9	1683.51	16.2	0.05	0.81

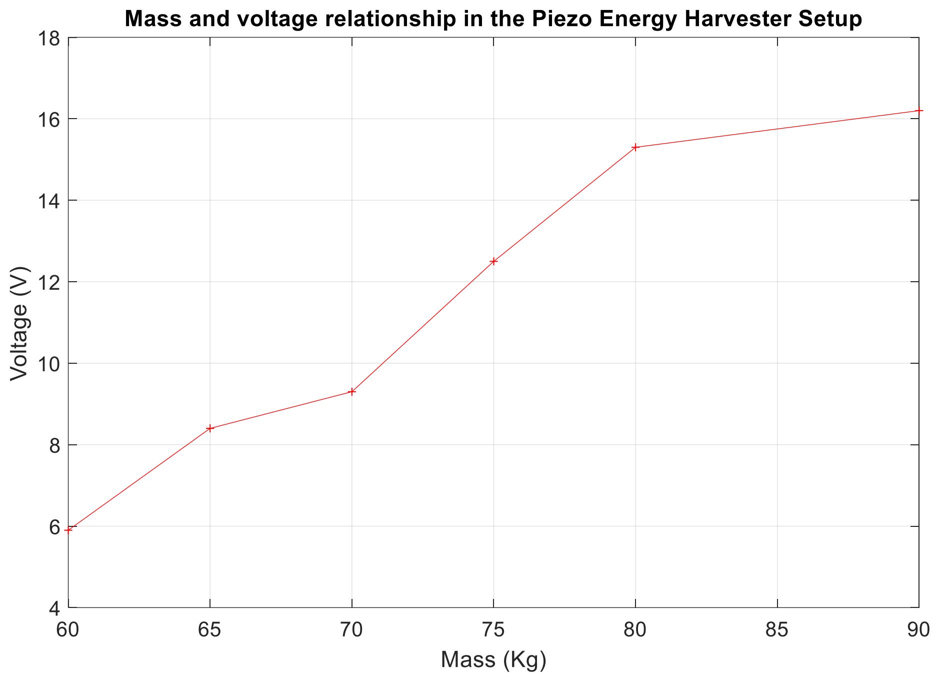

Figure 4: Voltage – Mass Relationship of the Energy Harvesting Device

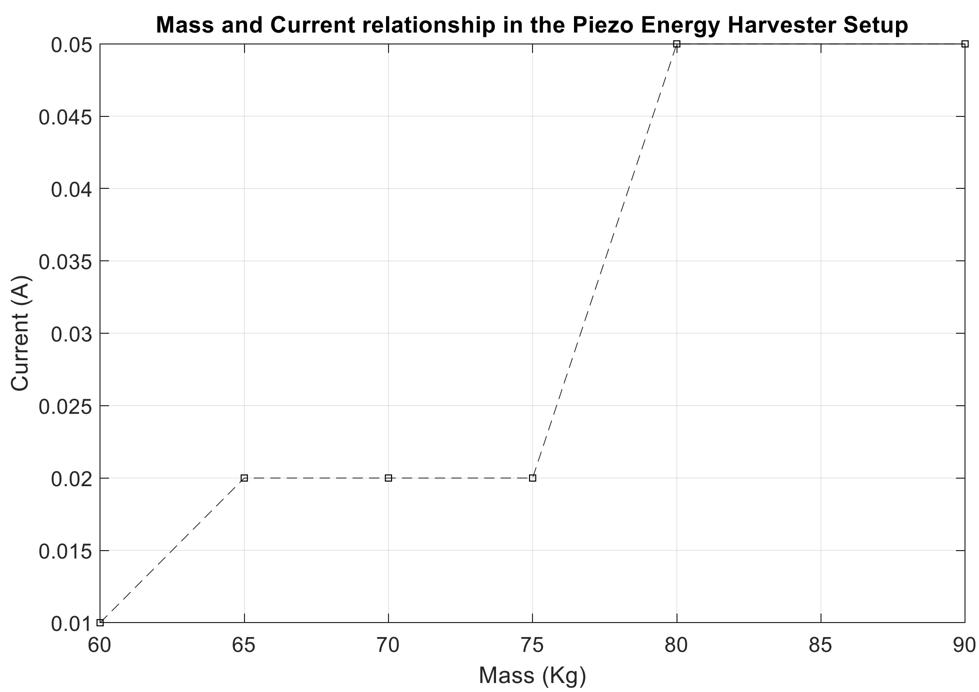

Figure 5: Current – Mass Relationship of the Energy Harvesting Device

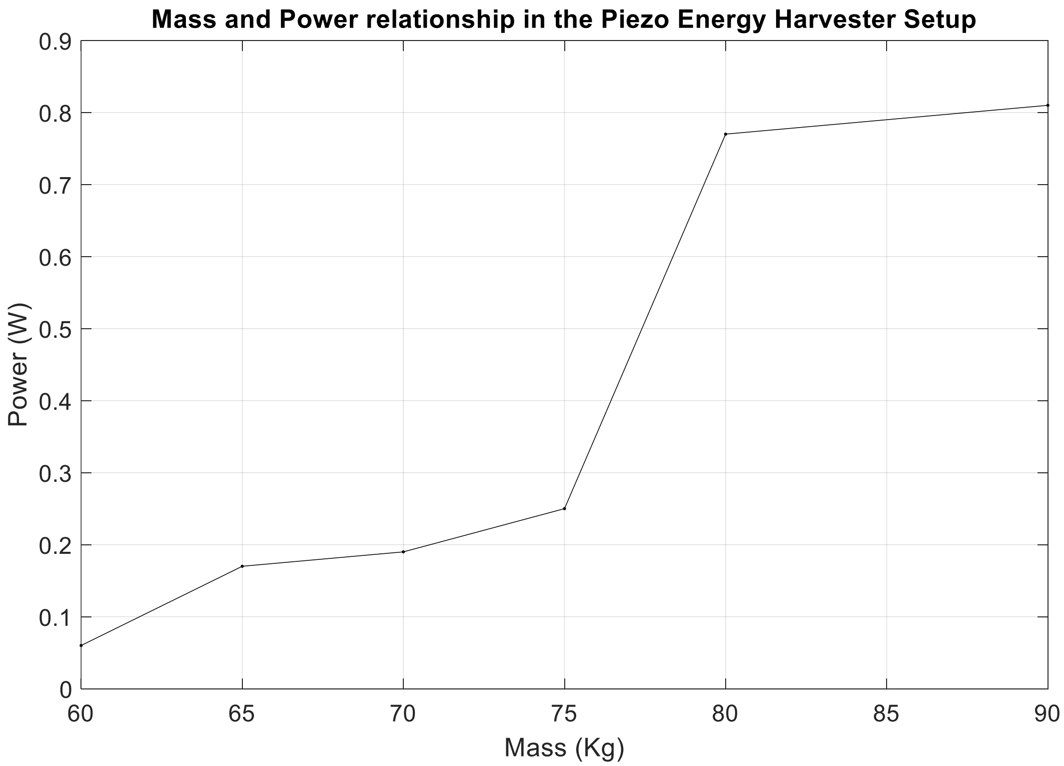

Figure 6: Power – Mass Relationship of the Energy Harvesting Device

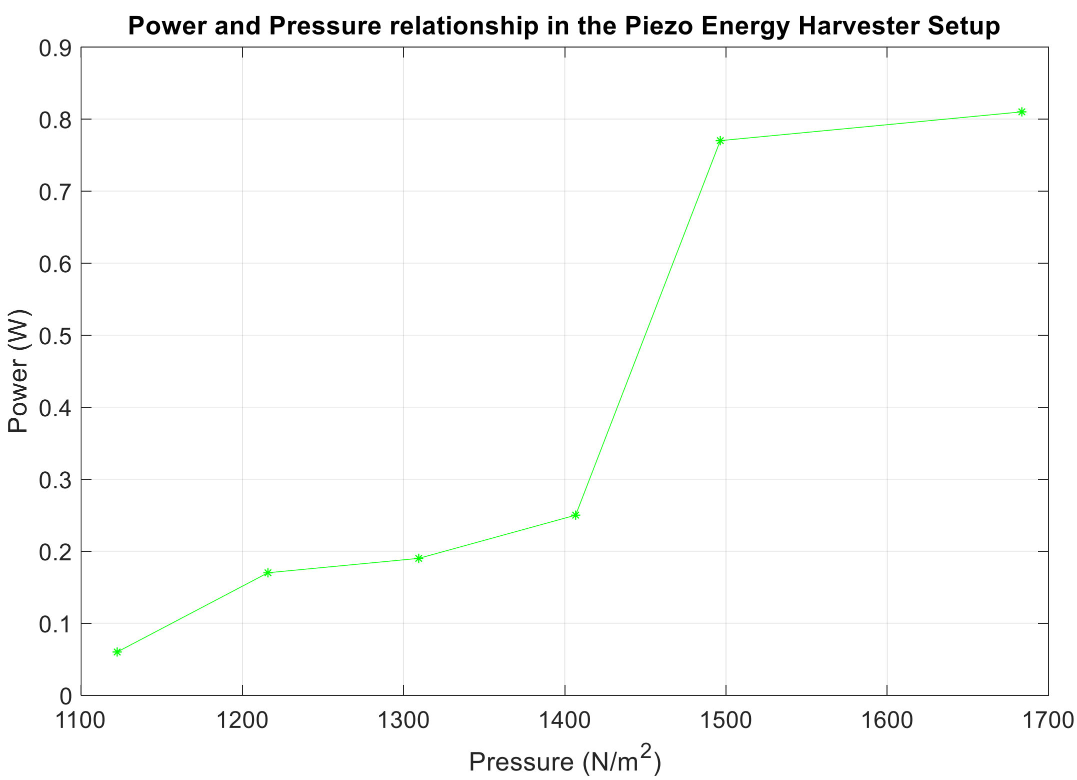

Figure 7: Power – Pressure Relationship of the Energy Harvesting Model

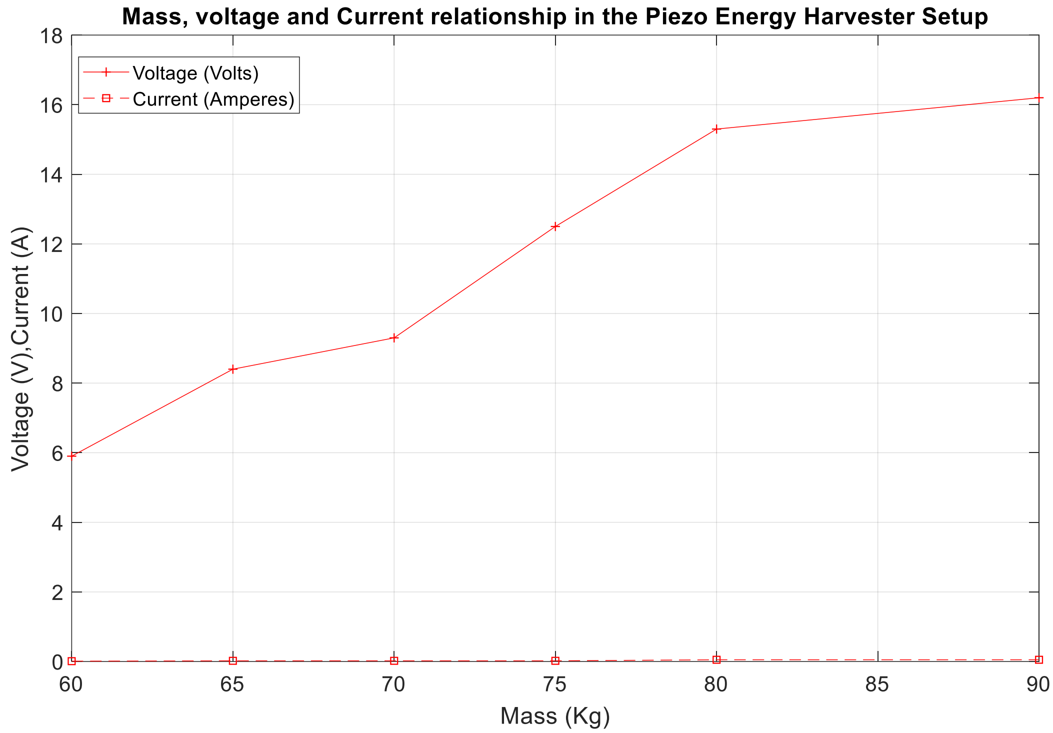

Figure 8: Current – Voltage Relationship of the Energy Harvesting Device

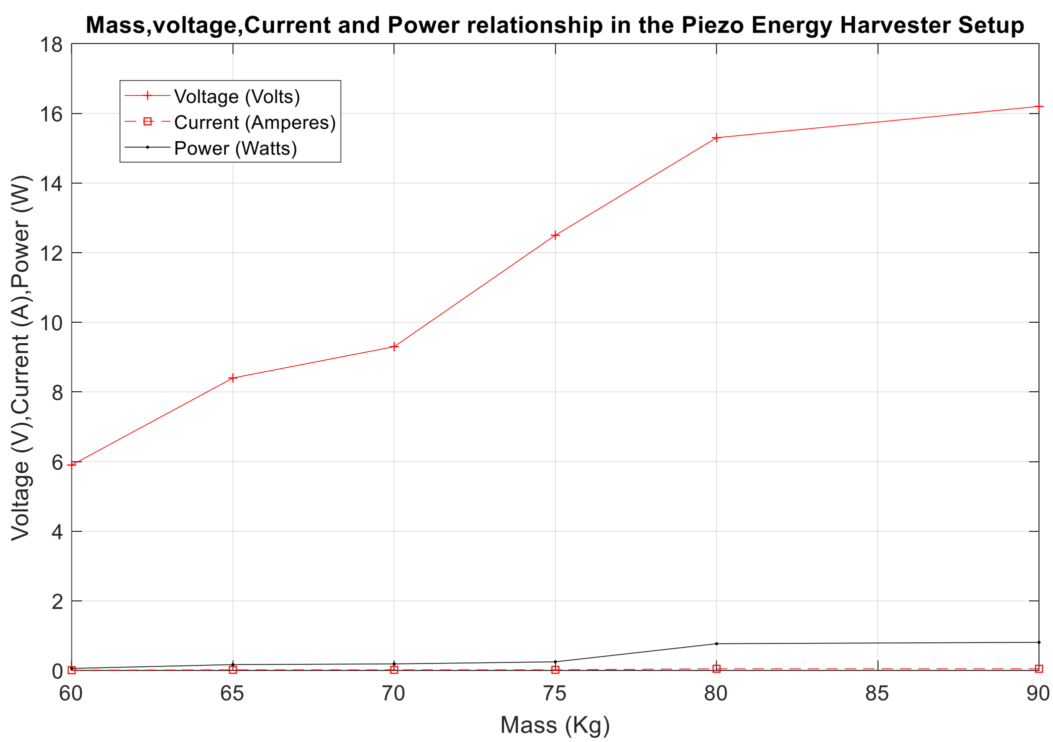

Figure 9: Power, Current, Voltage Relationship of the Energy Harvesting Device

Figure 4 presents the voltage – mass relationship showing appreciable increase in voltage value from 9.5V to 16.2 V as the mass increased from 60kg to 90kg. Figure 5 shows the relationship between current and diverse mass (kg) values at different intervals. The current value increased linearly from 0.01A to 0.02A with increasing mass of 60kg to 65 kg, then, attained a constant value up to 75kg and then, spike up to 0.05A when a mass of 80kg displaces the crystals, but with slow increase overtime. Figure 6 represents the changes in power generated from various mass applied at different intervals. Power increases steadily with an increase in mass up to 0.81W. Figure 7 represents the comparison of the output power and applied pressure, justifying the gradual increase in power output as pressure on the piezos increases. Figure 8 and Figure 9 depicts the comparison of the Voltage, Current and Power generated in relation to differing masses in the experimental setup of the energy harvesting model. These relations had been earlier separated in Figure 4 through 6 for ease of interpretation and clarity. Comparing the theoretical values in Table 1 to the values gotten from the experimental setup, referring to Table 2, the efficiency of the energy harvester can be computed.

$$\text{Efficiency of energy harvester} = \frac{\text{practical power}}{theoretical\ power} \times 100\%$$

The efficiency of the energy harvester is seen to increase appreciably with increasing pressure from 87.5% at 80kg to 92% at 90kg. This increase indicates at possible innovations in increasing pressure by mounting artificial vibration techniques to achieve intended efficiency which again offers more flexibility in this model design.

IV. CONCLUSIONS

From the proposed energy harvesting model, the amount of energy generated directly depends on the applied pressure while the voltage and current maximization follows directly from the series-parallel connection of the transducers. Comparing the theoretical and experimental power values, the efficiency of the energy harvester amounts to 92%. The 8% loss can be attributed to prototyping losses due to lags in component connection; which could be corrected for in large scale industrial integration. With increasing pressure, the power output can be maximized depending on specific application. Piezoelectric energy harvester has a very wide range of application that operates in densely populated areas. The implementation rigor of this means of renewable energy generation is minimal and the setup is of great importance as far as global ecosystem sustainability and conservation is concerned. Hence, with increasing pressure the power also increases until it reaches the maximum power, it can generate.

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