Foot Step Power Generation: A Comparative Analysis of Multi-Array Piezoelectric Transducer Configurations

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***Abstract*—Energy generation from green energy sources is gaining popularity day by day. Kinetic energy is produced while humans walk or run or jump and this energy can be converted into watt power with the help of piezoelectric transducers. One crucial aspect in this process is the configuration of different numbers of circular disc piezo sensors on the small area of the foot sole. This study aims to do a comparative analysis of the connection configuration of various piezoelectric sensors and determine the best output voltage and power achieved from footsteps. Additionally, the research aims to incorporate IoT to monitor the battery status. Four types of connection configuration of circular disc piezoelectric transducers on sole pads named series, parallel, series-parallel, and parallel-series topology have been designed and tested practically. Piezoelectric sensors of 35 mm dimension with a thickness of 3.36 mm are chosen and there are eight piezo sensors placed on the sole pad in a manner where the exerted pressure is maximum. With a very simple energy harvesting circuit devoid of boost converter and voltage regulator the experiment has been conducted. The investigation revealed that a single step on the sole pad, exerting a pressure of 686.7 N, can generate a maximum of 25 V in both parallel topology and parallel-series topology configurations. Conversely, the series topology exhibits the lowest converted voltage in comparison to all other configurations. But in the case of charging the battery by giving approximately 1000 steps the stable configuration is reported as parallel topology having the maximum dc current and power. The findings will help to select the right configuration for application in low-power-consuming devices like portable health care electronic devices, batteries, and sensors.**

***Index Terms*—Multi array sensor configurations, Foot sole power generation, Piezoelectric transducer, , Battery Monitoring, IoT.**

I. Introduction

Our daily needs for energy are greater than our ability to produce it. Due to scarcity of fossil fuel alternative ways of producing electricity is gaining popularity. The process of converting renewable energy sources, such as solar, thermal, wind, and vibrations energy, into usable electrical energy is becoming more and more common. One of them is harvesting kinetic energy from walking which can be converted into watts with the aid of piezo sensors [1]. A piezo transducer can convert the high amounts of kinetic energy produced by walking or running into analog electricity and capturing this energy is known as energy harvesting. The need for energy harvesting from the environment has dramatically increased due to the low power generation of these piezo ceramic, PZT (lead zicronate titanate) in recent years as a result of the low power requirements for the operation of micro sensors, actuators, low powered portable and wearable devices [2]. Piezoelectric materials with low power output have the ability to capture energy from foot step pressure, which is easily accessible during human walking [3]. Yi Xin *et. al* [4] reviewed the key findings of various types of shoe equipped energy harvesters based on piezo transducers especially for PZT and PVDF. While in *Nilimamayee Samal et.al* [5]work, the various kind of configurations of piezo transducer has been detailed which are suitable for any kind of vibrations and environmental sources. Multiple works are there showing conversion of kinetic energy into electrical energy using various forms of piezo sensors with energy harvesting system in foot wear. Various challenges still exist to get optimum output power from extorted pressure of human footsteps with a sustainable and reliable energy harvester circuit. While connecting more than one piezo sensors to generate maximum power appropriateness is needed since the transducer output is affected by phase and frequency variations. *Ali Ekber Zdemir et al* [6] in his research charged a capacitor in parallel, serial-serial-parallel, and serial connections considering a piezo sensor as an ideal source. Using rectification for each piezo sensor output the maximum output voltage they obtained was 9.9 V for the proposed serial-serial-parallel circuit topology. Another research work by *Nik Ahmad Kamil Zainal Abidin et.al.* [7] Concentrated on multiple circular piezo in the form of discs linked in parallel, series, and series-parallel configurations. Simulated results have high output voltage for series-parallel and parallel-series configuration in multiple numbers of piezo sensors. The combination of the piezo sensor connections was found to have an advantage over using single piezo sensors in terms of the harvested output power. Another array configuration technique based on more than one number of low frequency PZT-5A has been simulated in Multi-sim Software in the work of *Liew Hui Fang et.al* [8]. It asserted that, one unit have less voltage than five units of piezo sensors and the Vrms increases with variable load resistances connected in parallel connection

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in comparison to series connection. Additionally, few works incorporated IoT (Internet of things) to foot step energy harvester for monitoring generation of electricity. The use of IoT in monitoring battery storage condition or smart street lights powered by piezoelectric sensors has been implemented and successful results were demonstrated in IoT dashboard [9-10]. However, in total there is no such presentation of real experiment comparing the connection topology with 8 units of piezo sensors placed on foot sole at the right position of exerted human pressure. In this paper, to conclude the optimum output voltage of multi array configuration of piezo sensors in foot wear simulation as well as hardware implementation has been shown. The typologies of piezo sensor connections have been incorporated into shoe soles to generate electricity. A person's weight and the number of steps taken over time on the shoe soles recorded to compare the different connection configurations in generating sufficient power. With a simple energy harvesting circuit, battery's state of charging or discharging with an IoT has been implemented as well.

II. METHODOLOGY

A. *Working Principal*

The ability of piezoelectric materials to produce an electric charge as a response to mechanical stress is known as the piezoelectric effect. The crystal structure is a characteristic of piezoelectric materials. They have the capacity to transform mechanical energy or any stress or vibration into electrical energy. The overall working principal of the design in this work is presented in Fig.1. Four main types of connection configuration are placed on separate foot soles and mechanical stress of different weights has been implemented. The generated alternating current (AC) signal after passing through a bridge rectifier is converted to direct current (DC). The wires from the output of the rectifier are connected to a capacitor for filtering DC output. To ensure one directional current flow diode has been used before the battery. IoT technology has been incorporated to monitor battery charging and discharging in an intelligent way.

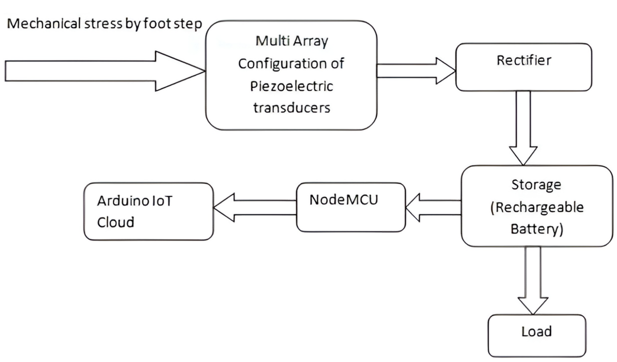

Fig. 1. Block diagram of the System

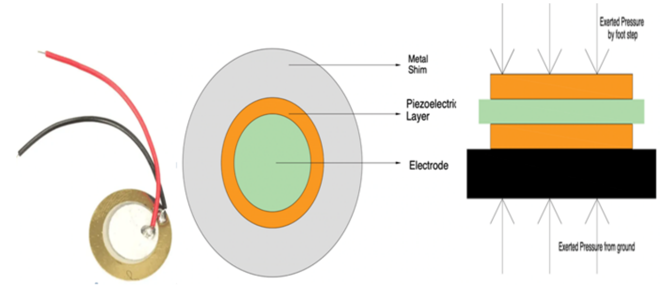

Fig. 2. .
(a) Ceramic Piezo-electric transducer (b) Circular Diaphragm Transducer (c) Planar Diagram

B. *Structural Design*

Piezoelectric sensors utilize materials such as lithium niobate, quartz, or lead zirconate titanate (PZT) to generate voltage in response to pressure. Here circular disc-type ceramic piezoelectric transducer has been used as shown in Fig. 2. The initial stage involves creating a detailed CAD design of the prototype within the shoe sole. This aims to provide a clear visual representation of the prototype's framework, as depicted in Fig. 3.

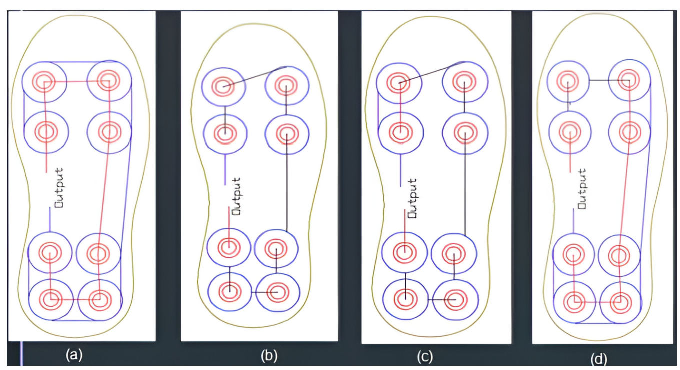

Fig. 3. (a) Parallel Connection (TP1) (b) Series Connection (TP2) (c) Series-Parallel Connection (TP3) and (d) Parallel-series Connection (TP4)

It shows the placement of the 8 units of piezoelectric sensor at the front of the foot and around the heel area of the foot sole where variable weight applies maximum pressure and produces optimum output in a typical walking gait.

PZT materials are chosen for this experiment due to their exceptional piezoelectric characteristics, broad frequency responsiveness, stability, and ready commercial accessibility, despite their brittleness and the substantial forces involved. We employ appropriate design methodologies and safety measures to address the challenges associated with PZT.

C. *Calculating Energy Generation in Ceramic Crystals*

An assessment is needed to know how much energy the piezoelectric transducer can produce to meet up the energy requirement of daily application. As per the findings by Rocha et.al [11], running a heart rate monitor for an hour consumes 3J of energy, similarly, a respiratory rate meter uses 3J, an MP3 player requires 350J, a mobile phone on standby consumes 150J, and a phone conversation uses 2800J. This assessment includes the energy generation within the crystal and the energy produced from footsteps which have been detailed through mathematical calculations conducted by S. Krishna and S. Vignesh [12].

The voltage generated in the crystal [12]

$$E = g_{31} \cdot t.P \tag{1}$$

where g_{31} is the voltage sensitivity of the piezo whose value is 10×10^{-3}, and t is the thickness of one crystal is 3.36mm and p is the pressure exerted on the piezoelectric transducer crystal. The pressure is the force exerted by a human walk/area of the crystal. The exerted force by human walk is Weight × acceleration (let, $70 \mathrm{~kg} \times 9.81 \mathrm{~ms}^{-2}$) which is 686.7 N due to gravity. The circular disc of diameter 35 mm has been used. So the pressure is

$$P = \frac{\text{Exerted force}}{\Pi * 17.5 * 17.5 * 10^{-3} 10^{-3}}$$

$$P = 0.687 \times 10^{6} \mathrm{~N/m}^{2}$$

Thus, the voltage being generated in theoretical calculation from equation (1) is

$$E = 10 \times 10^{-3} \times 3.36 \times 10^{-3} \times 0.687 \times 10^{6}$$

$$E = 23.0832V$$

The energy generated per step is

$$E = 686.7 \times 0.001 = 0.6867 \mathrm{~J/ ~step}$$

Since some of the pressings of steps might not give the maximum energy due to variation of pressure, the theoretical energy should be calculated by considering 50 percent of the obtained energy. Therefore, the half energy in a one-foot step is 0.3434 J and 11.5416 V. The consequent two steps by the feet produces 0.6868 J.

Energy (kWh) = 0.6868 J / 3,600,000 = 0.0000001908 kWh

Energy per day (kWh/day) = 0.0000001908 kWh * 86,400 seconds = 0.0000165 kWh/day. Walking for around thirty minutes and taking approximately 1000 steps yields an energy output of about 0.0164 kWh per day. Increasing the number of steps and expanding the implementation would lead to greater daily energy generation.

The subscript ”31” in ”g31” denotes the correlation between mechanical stress applied in the 3-direction (perpendicular to the material surface) and the resulting electric charge produced in the 1-direction (parallel to the material surface). In the context of foot stepping, this signifies that the piezoelectric material experiences stress in a direction perpendicular to its surface, potentially due to compression or deformation caused by the footstep. Consequently, it generates electric charge in a direction parallel to its surface.

The choice of ”g31” for a foot stepping energy harvesting the device is based on aligning the mechanical stress direction induced by the footstep with the orientation of the piezoelectric material in the system. This strategic selection aims to optimize the conversion of mechanical energy from foot pressure into electrical energy by leveraging the piezoelectric effect.

To summarize, ”g31” is employed to describe the piezoelectric response in a specific direction, and its utilization in foot stepping energy harvesting is likely aligned with the mechanical stress patterns generated by foot pressure during walking or other activities.

D. Circuit Simulation

The simulation was conducted utilizing Proteus 8.7 due to the nature of the components involved in the project. A piezo-electric sensor simulation file for Proteus simulation has been used here as a demo. All the connection configuration types were first simulated to have an overall scenario of the comparative analysis.

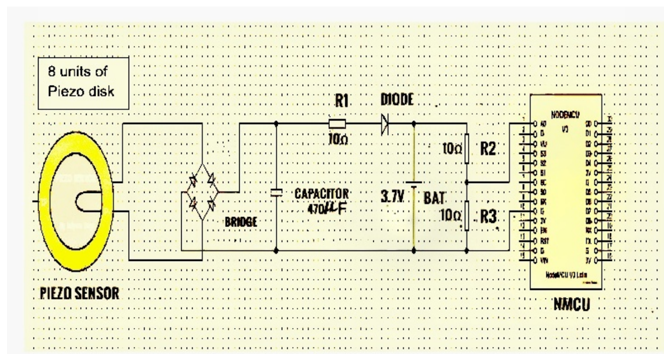

Fig. 4. Circuit Diagram

III. Implementation

The execution of the project was handled delicately to ensure the integrity of all components without causing any damage. The general specification of Ceramic Piezo sensors implemented are tabulated in Table I. Figure 5 shows the placement of 8 units of the piezo-electric sensor on the upper part of the shoe sole. The covered part which is placed under the feet has been attached with a cork sheet to have the exerted pressure at the right position of the piezo sensors. A bridge rectifier with silicon diodes was further connected to the capacitor and a resistor. The IoT was connected including a battery.

TABLE I
General Specification of Piezoelectric sensor:

Name:	Rating/measure:
Thickness:	3.36mm
Diameter:	35mm
Resonant Frequency:	10+/-0.5KHZ
Operating Temperature:	-20 ∼70
The Input Voltage:	30V p-p max
Shipment Weight:	0.007kg

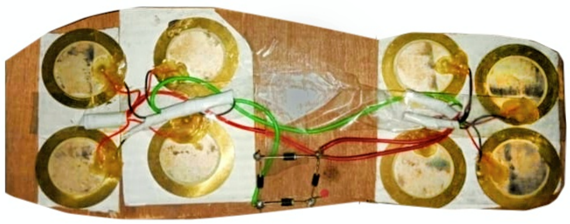

Fig. 5. Experimental Setup of eight unit piezo sensors connected in parallel configurations

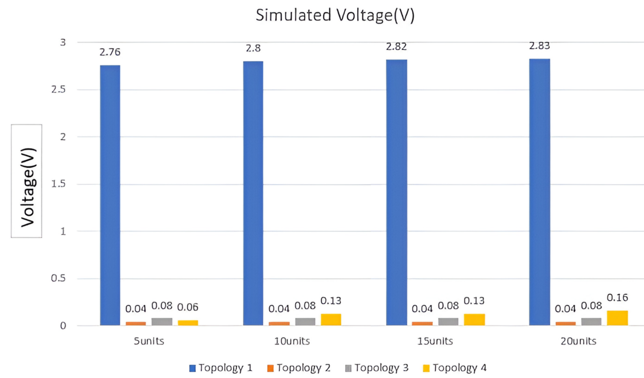

Fig. 6. Simulated Voltage of Different Connection Configurations

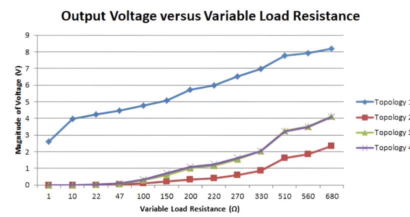

Fig. 7. Change in the magnitude of voltage with load resistance for 15 units of piezoelectric sensors

IV. Results and Analysis

A. Simulation Results

The simulation has been done in Proteus 8.7 using the piezoelectric transducer library model. This specific model has a maximum rated voltage of 2.83 V. Four distinct types of topology were separately simulated. Here a push button acts to give the mechanical pressure on the piezoelectric transducer. Initially, simulations were conducted using a single piezoelectric transducer, and subsequently, an array of piezoelectric transducers ranging from 5 units to 20 units of circular disks were employed. The primary objective was to compare the voltage output for different typologies, as outlined in Table II.

TABLE II
Simulated Maximum DC voltage for different units of Piezoelectric Transducers

Name of the topology	Obtained voltage from simulation			
	5units	10units	15units	20units
Topology 1	2.76v	2.80v	2.82v	2.83v
Topology 2	0.04v	0.04v	0.04v	0.04v
Topology 3	0.08v	0.08v	0.08v	0.08v
Topology 4	0.06v	0.09v	0.13v	0.16v

In Topology 1, where piezoelectric transducers were connected in parallel, an increase in the magnitude of voltage was observed with an escalation in the number of piezoelectric sensors. The highest recorded Vrms value was 2.83 V for the configuration with 20 units connected in parallel. When piezoelectric devices are connected in parallel, the voltage stays nearly constant but the sum of the individual currents causes a rise in the overall current. This behavior is a feature of parallel electrical connections, and when designing circuits with parallel connections, it's critical to take the application requirements and the electrical properties of the piezoelectric devices into account.

In contrast, the other connections, which included series, series-parallel, and parallel-series, did not exhibit substantial alterations in the output voltage despite changes in the number of piezoelectric sensors. The charge produced by one piezoelectric sensor in a series connection can indirectly affect the behavior of other sensors due to the coupling effect as there is no isolation between them in this connection. This limits the efficiency of power generation in series-connected piezoelectric devices. The total current output of parallel-connected piezoelectric sensors is additive resulting in high voltage output with the greater number of piezo sensors.

The graphs in Fig. 7 illustrate that the output voltage varies based on the variable resistor's value for all types of connection configurations. In the case of the parallel connection the reported maximum voltage at 1Ω is 2.62205 V, which significantly increases to 8.2 V when the resistor value reaches 680Ω. For Topology 3 and Topology 4, which involve a combination of series and parallel piezoelectric sensors, the output voltage behaves similarly with changes in load resistance, reaching around 4.14 V and 4.08 V at 680Ω, respectively. On the other hand, Topology 2, representing series-connected sensors, exhibits the lowest voltage output at 680Ω.

Topology II and III have constant output from 5 units to 20 units, series connection of the current source is the cause of the consistent voltage output. When the current sources are linked in series, the output voltage will be produced at the same output even with numerous more current sources. The expected decreased current output in a series connection would affect the power output of the associated piezoelectric. When the sources are linked in series, the maximum power output does not change due to the coupling effect of the internal capacitance piezoelectric. A piezoelectric is a con server device, therefore whatever charge it generates is impacted indirectly and will dissipate through another conserve piezoelectric since there is no isolation between piezo electrics when they are linked in series.Consequently, increasing the number of piezoelectric elements in series will not increase the power output because the resulting power level will remain the same. Due to the coupling effect, the maximum number of sensors in series for topology 3 also provides the same output voltage.

V. Experimental Results

Eight piezoelectric transducer units were appropriately connected and positioned on the foot sole, as illustrated in Figure 8. Various weights were applied during the experiment, and measurements of voltage, current, and power were taken for a single step and over an approximate duration of 30 minutes, corresponding to about 1000 steps. Stepping on the designed sole with a weight of 70 kg resulted in a DC output voltage of 25 V, a current of 2 mA, and a power of 50 mW per step. The battery charge stored was recorded at 0.07 V for 1000 steps(Shown in Fig. 10).

Comparing power outputs, the 60 kg weight scenario exhibited higher power generation (32 mW) than the 50 kg weight scenario (18.6 mW), indicating that greater weights can yield more electrical energy through the piezoelectric transducer system. Furthermore, the battery's charge stored for the 60 kg weight (0.05 V) was higher than that for the 50 kg weight (0.04 V) over 1000 steps.

After 1000 steps, the battery charge stored was recorded 0V, with an output voltage of 1.5 V, a current of 0.01 mA, and a power of 0.015 mW for Topology 2. Similarly, with 63 kg weight, the battery charge stored stayed unchanged, displaying an output voltage of 1.3 V, a current of 0.01 mA, and a power output of 0.013 mW per step. Notably, there were no significant battery status changes even after an hour of walking with shoe soles equipped with series-connected piezo sensors.

A hybrid connection comprising 6 sensors in series (6S) and 2 sensors in parallel (2P) was implemented to assess the performance of a series-parallel connection. The initial application of a 70 kg weight for Topology 3 resulted in an output DC voltage of 20 V, a current of 0.1 mA, and a power of 0.020 mW, with the battery charge stored recorded at 0V. Similarly, at 63 kg, the output DC voltage was 18 V, with a current of 0.001 mA, a power of 0.017 mW, and a stable battery charge stored status for 1000 steps. Walking with 60 kg yielded a constant battery charge status, producing 17 V output voltage, 0.01 mA current, and 0.017 mW power for each step. Applying a 50 kg weight resulted in a stable battery charge stored status, generating an output voltage of 15 V, a current of 0.01 mA, and a power of 0.015 mW for each step.

In Topology 4, piezoelectric transducers were connected in series (2S) and parallel (6P). For a 70 kg weight, the output DC voltage was 25 V, with a current of 1.3 mA and power of 32.5 mW. The battery charge changed by 0.006 V for 1000 steps. At 63 kg, the output voltage was 23 V, with a current of 1 mA, and a power of 23 mW, and the battery charge stored was recorded at 0.004 V for 1000 steps. For a 50 kg weight, the battery charge was stored at 0.002 V for 1000 steps, yielding 18 V output voltage, 0.7 mA current, and 12.6 mW power for each step.

TABLE III
ALL TOPOLOGICAL MAXIMUM OBTAINED VOLTAGE FOR DIFFERENT KINDS OF WEIGHT WITH 8 UNITS OF PIEZOELECTRIC SENSORS BY USING SINGLE STEP

Weight(Kg)	Name of the Topology			
	Topology1	Topology 2	Topology3	Topology4
70	25v	1.6v	20v	25v
63	23.5v	1.5v	18v	23v
60	20v	1.3v	17v	22v
50	15.5v	1.1v	15v	18v

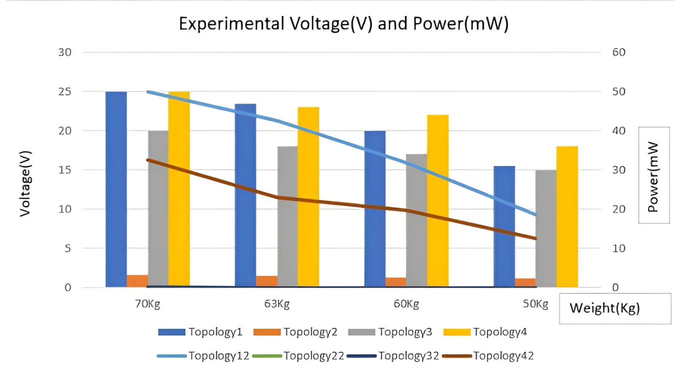

Fig. 8. Experimental maximum gain voltage(V) and Power(mW).

A storage device can be charged using parallel typologies because it has chargeable voltage, current, and power. Additionally, charging a storage device using a parallel topology needs less effort. Lower voltage, current, and power are produced by other side-series typologies. The voltage in the series-parallel combined topology is sufficient, but the current is insufficient, and no storage devices can be charged. High voltage is also produced by parallel-series combined topology, but current and charge storage rates are less than from parallel topology. Therefore, to store the full charge, parallel-series topology requires more steps than parallel topology. The best topology for creating energy-harvesting devices is now clear: parallel topology. The status of the battery was continuously monitored in the IoT dashboard depicted in Fig. 9.

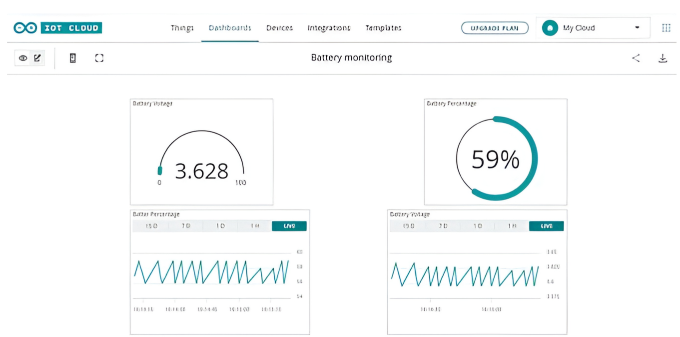

Fig. 9. IoT dashboard for battery status monitoring system

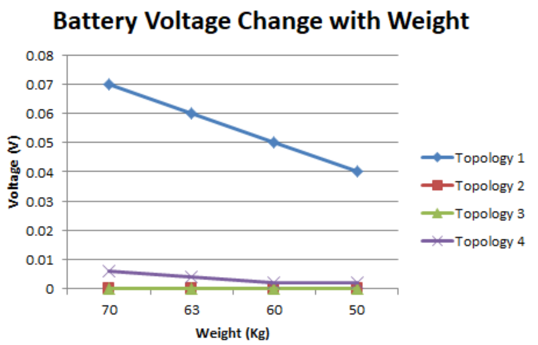

Fig. 10. Change of Battery Voltage Status with Weight taking 1000 steps

VI. Conclusions

The process of generating electricity while walking has gained attention in the last decade. It is very important to select the piezo sensor number and connection configuration designed for footwear to achieve optimum output with an efficient energy harvesting circuit. This work presents both simulated and experimented results to conclude the best configuration of multi-array piezo transducer connection.

Simulation results based on the model piezo sensor of Proteus Software showed parallel topology with the highest output voltage. In the case of the experiment, the pressure exerted and the number of footsteps are counted to find the voltage, power, and current of the typologies. With 8 minimal number of sensors placed at the heel and ball of the foot, parallel topology generates 25V for a single step with exerted pressure from 70 kg weight. Again to charge the battery of 1300 mAh of 3.7 V with 1000 steps approximately 26.5 hours are required. Since no boost converter has been used here the lower voltage counted needs much more time to charge the battery fully. With energy harvesting circuit limitations, with the increased number of users and steps this footstep power generation can be a good contribution to modern society.

The advancements of these technical developments in footstep energy harvesting devices are to increase the efficiency of energy conversion, enhance practicality and durability, and facilitate integration into embedded and wearable systems. These technologies provide self-sufficient and sustainable applications across a range of industries, such as wearable technology, smart infrastructure, and Internet of Things devices, by using the energy from footsteps. Footstep energy harvesting systems convert human footfall into electrical energy, providing a renewable and sustainable power source for wearable technology. This technology is particularly useful in rural areas, outdoor events, and emergencies. It can also power infrastructure elements like sensors and lamps, aiding in smart cities. Additionally, it offers an affordable and decentralized way to generate electricity in areas with inadequate infrastructure, enhancing energy access in underdeveloped nations where reliable power sources are difficult to find.

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