Materials Physics and Mechanics 37 (2018) 159-167 Received: December 22, 2017

# PIEZOELECTRIC BASED ENERGY HARVESTER EMBEDDED IN SHOE FOR WEARABLE ELECTRONICS

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**Abstract.** Piezoelectric based energy harvesting has become a popular research interest for last few years. This is due to the increasing demand for low-powered portable and wearable electronic devices such as health monitoring sensors. This paper presents two polyvinylidene fluoride (PVDF) based energy harvesters, which can be embedded in shoes to generate electric energy while human walking. One of the harvesters is specially designed as a sandwich structure, placed under the ball of foot, while the other one has curved or oval-shaped structure, placed under the heel of foot. Both harvesters are developed and deployed appropriately in the sole to couple maximum mechanical stress to the piezo-material and achieve high power output. The system was analysed, using mathematical modelling and results are verified by performing experiments in the lab. It has been observed experimentally that sandwich structured harvester produces 4.9 μW across a capacitor of 10 μF while walking at a speed of two step/second (2 Hz). However, for the same capacitor, the curve-shaped harvester produces up to 5.625 μW power. Integrated output power of both energy harvesters was 9.625 μW.

**Keywords:** piezoelectric; energy harvesting; PVDF; walking motion; smart materials.

## 1. Introduction

Energy harvesting technique has been an area of immense interest in research area of Harvesting energy from the energy sources such as heat, light, vibration and motion is an agreeable approach for acquiring the clean and sustainable energy. Energy harvested from vibrations and oscillations for instance low frequency vibration is the best method of energy harvesting [1]. The research motivation of this work is due to need of reduction in power requirement of low power consuming electronic devices, such as wearable and bio MEMS devices. A certain amount of electric current or voltage can be retrieved on application of mechanical strain on piezoelectric materials. Mechanical strain can be produced from different sources such as human body movements, seismic vibrations, machine bed vibrations and acoustic sound generally available everyday [2]. Two energy harvester designs using polyviyldine fluoride (PVDF) have been discussed in this work. One of the sandwiched structures is placed under the ball of the foot. Other one is curved shaped structure and placed under the heel of the foot. Modelling and experiments have been performed for both energy harvesters. Also, comparison of two polyvinylidene fluoride (PVDF) based energy harvesters have been done, which can be embedded in shoes to generate electric energy while human walking. In 2005 Sodano and Inman et al. [5] identified piezoelectric material as a tool for energy generation. They experimented the abilities of a circuit comprising a rectifier and a storage capacitor, when a steel ball impacted a plate bonded with PZT. In 2006 Sodano and Inman et al. [6] studied and developed a piezoelectric system to harvest the energy while

http://dx.doi.org/10.18720/MPM.3722018_8

human walking and power a 12-bit RFID at 310 MHz. They developed a PZT bimorph. The peak output power from that PZT bimorph in $d_{31}$ bending mode under heal was 8.3 mW and from PVDF stave under toes was 1.3 mW.

**Overview of Energy Harvesting System.** The piezoelectric energy harvesting shoe system is able to harvest the energy from two points of contact during walking, which is shown in Fig. 1. The first point is the ‘Contact Phase’, which will obtain at the time of heel strikes during foot landing. At this point, energy is harvested by energy harvesting shoe system through compression of the piezoelectric material. The second point is the ‘Propulsive Phase’, which will obtain when the ball of the foot bends after landing the tip of the shoe to propel the person forward. The system consists of placing two piezoelectric (PVDF) energy harvesters at those two appropriate points for harvesting the maximum output energy.

**Fig. 1.** Foot phase description while walking.

## 2. Design of sandwich type piezoelectric energy harvester

The main structure of this piezoelectric energy harvester is a sandwich type structure, where a multilayer Polyvinylidenefluoride (PVDF) film stack is sandwiched between two wavy surfaces [13]. One of these surfaces is a movable upper plate and other one is a fixed lower plate as shown in Fig. 2. Double PVDF film stack is fixed on the lower plate, and these PVDF Films are connected in series to obtain maximum output voltage.

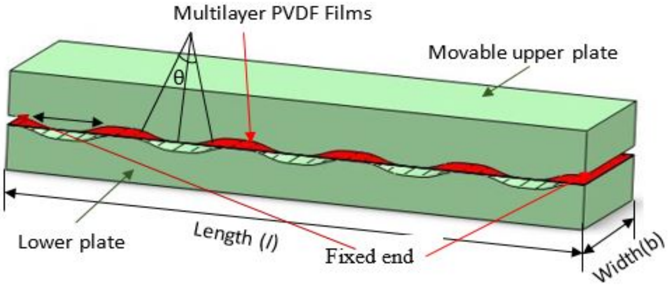


**Fig. 2.** Solid work model of energy harvester.

**Working mechanism of energy harvester.** The energy harvester works, when the upper movable plate of the piezoelectric energy harvester is subject to a compressive force, produced by human foot. The upper plate of energy harvester moves down and the PVDF film is stretched along the longitudinal (*1*-axis) simultaneously that is shown in Fig. 3. Due to stretching the PVDF film in longitudinal direction, strain is developed inside the film. This strain leads to a piezoelectric field inside every PVDF layer. The strain, developed in the PVDF film, drives the free electrons inside the each PVDF film. The external circuit is used to accumulate charge on the upper and lower surfaces of piezoelectric PVDF film, which has the electrode. Then it induces the piezo potential in three-axis surfaces (electrodes) of every PVDF layer. When the foot force is released, then the upper movable plate moves up and the PVDF films relax and get original shape, therefore the piezopotential diminishes, and also releases the accumulated electrons on the surface of PVDF films. When human walks the dynamic force is produced by foot. This force acts on the upper plate that drives the electrons inside the piezoelectric layer surface and induces an alternating current (AC) output.

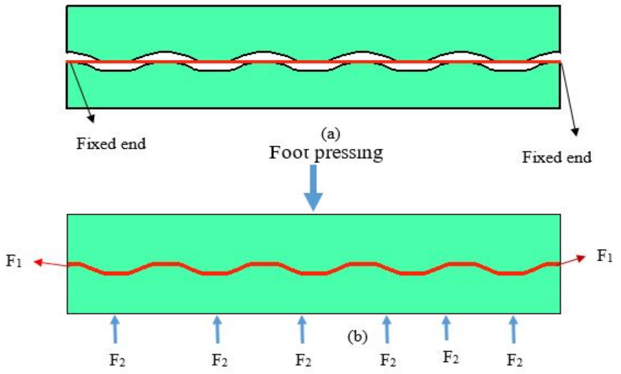


**Fig. 3.** Working mechanism of harvester.

The specially designed harvester's wavy surfaces are able to produce the large longitudinal deformation in the PVDF films and it reduces the thickness of piezoelectric energy harvester, which improves the energy harvesting performance and this harvester makes it possible to embed the harvester into a shoe.

Table 1. Design parameters of sandwiched type energy harvester.

| Parameter name | Value | Description |
|---|---|---|
| $L$ | 70 mm | Harvester length or PVDF layer length |
| $W$ | 20 mm | Harvester width or PVDF layer width |
| $T$ | 28 µm | PVDF layer thickness |
| $A_1 = wt$ | 0.56 mm$^2$ | Cross-section area of one PVDF layer |
| $A_3 = wl$ | 1400 mm$^2$ | Three-axis surface area of one PVDF layer |
| $N$ | 2 | Number of PVDF layers |
| $l$ | 11 mm | Chord length of arc-shaped groove |
| 2θ | 36° | Intersection angle of an arc-shaped groove |
| $n$ = INT($l$/$L$) | 5 | Number of arc-shaped groove |

According to the elastic limit of the PVDF film, the design parameters of energy harvester have been developed (see Table 1). When movable upper plate moves down to the lowest position, both the tension of multilayer PVDF film $F_1$ and the resistive force $F_2$ against the upper plate, produced by (PVDF) film, reach maximum.

**Mathematical modelling.** Mathematical modelling of the harvester includes the equations for tension force $F_1$:

$$F_1 = NA_1\sigma_1, \tag{1}$$

where $\sigma_1 = \varepsilon_1 Y$ is the normal stress and for normal strain $\varepsilon_1$:

$$\varepsilon_1 = \left(\frac{\theta}{\sin\theta} - 1\right). \tag{2}$$

Equation (2) shows the dependence of the strain, generated in the harvester design, on the semi-intersection angle, $\theta$ [13], which is present in Fig. 4.

Since the elastic limit of PVDF is 2%, maximum permissible limit of $\theta$ is equal to 19.71°. Keeping a safety margin of 1.2 in the strain developed, for further analysis of $\theta$, we adopted this limit as 18°. For simplicity of description, the frictions between the PVDF film and the wavy surfaces are ignored for calculating the resistive force.

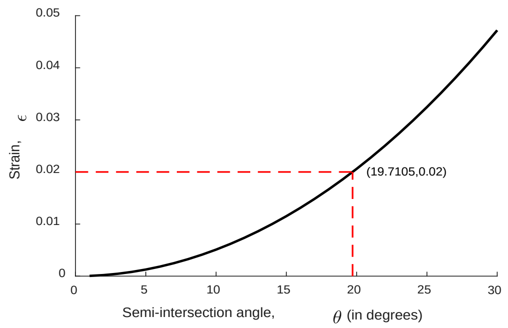


**Fig. 4.** Strain variation *vs* the semi-intersection angle of arc-shaped groove.

Resistive force $F_2$ is defined as:

$$F_2 = n \cdot 2F_1 \sin\theta = (l/L) \cdot 2NA_1\sigma_1 \sin\theta; \tag{3}$$

$$F_2 = 2Nwn(l/L)(\theta - \sin\theta)Y. \tag{4}$$

The constraint conditions for the design are presented as:

$$\varepsilon_1 = \left(\frac{\theta}{\sin\theta} - 1\right) \le \varepsilon_e; \tag{5}$$

$$F_2 = 2Nwn(l/L)(\theta - \sin\theta)Y \le \text{foot force}, \tag{6}$$

where $\varepsilon_e$ is the elastic limit of the PVDF film, the value ranges of the above design parameters can be determined, based on the requirements of a specific design.

**Energy extraction circuit.** Power extraction circuit consists of two piezoelectric sources (MB10S), connected in series; rectifier with four Schottky diodes, used in high switching application; 1.2 MΩ resister and a 10 μF capacitor (see Fig. 5).

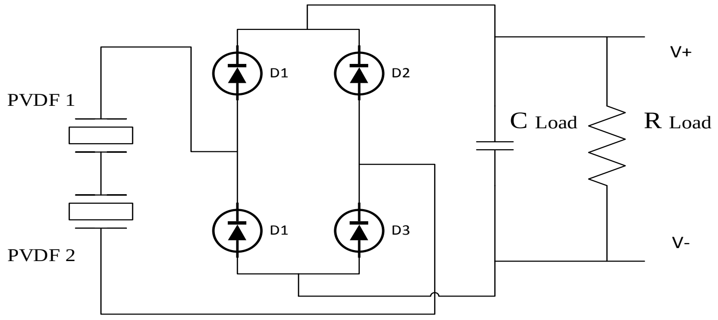


**Fig. 5.** Energy extraction circuit

**Fabricated model of energy harvester.** The fabricated model (see Figs. 6 and 7) consists of two rubber plates and two layers of PVDF films, glued with epoxy adhesive and sandwiched between two rubber plates therefore this harvester could be embedded under the foot force of shoe. The PVDF films have the electrodes and connection of PVDF films can be parallel and in series.

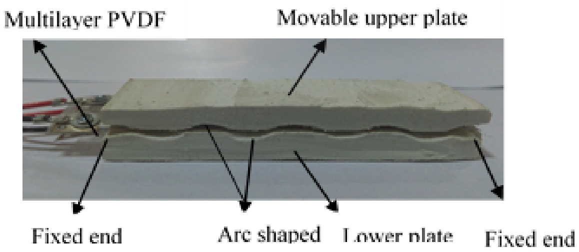
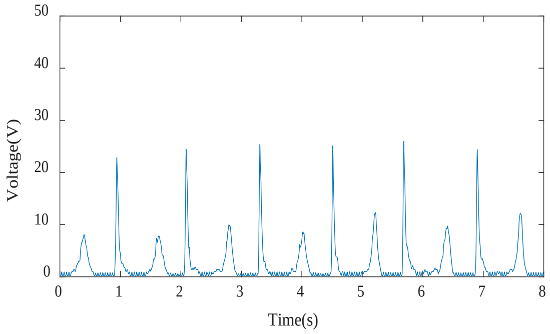


**Fig. 6.** Sandwiched structure.

**Fig. 7.** Experimental setup.

**Experimental results.** In this experimental setup, a person of 60 kg weight wears the shoe/sandal and then walks at the speed of 2 steps per second (2 Hz).



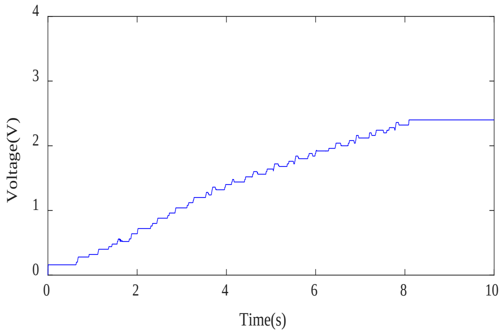


**Fig. 8.** Rectified voltage.

**Fig. 9.** Capacitor charging voltage.

Figure 8 shows the voltage across the 10μF storage capacitor. The capacitor will be fully charge after 15 steps and it induces approximately 2.5V DC output voltage (see Fig. 9).

## 3. Design and working mechanism of curved shaped piezoelectric energy harvester

When the piezoelectric energy harvesting device is pressed by external force in the middle, the PVDF and substrate are subjected to compressive and tensile stresses, respectively, therefore generating electric potential. In this harvester, the stress is produced in longitudinal direction and the electric field is generated in lateral direction. This curved piezoelectric generator consists of two separate curved piezoelectric generators, connected back-to-back, where each generator comprises a curved PI substrate and two polyvinylidene fluoride (PVDF) films [23]. The steel curved substrate is used to support the curved PI substrate and provide the appropriate flexibility during the human walking. The harvester consists of piezo 1 and piezo 2 which are made of PVDF and the electrodes of the both PVDF films are attached on both sides of the curved PI substrate, used in curved piezoelectric generator. Here, the curved piezoelectric energy harvester with top and bottom electrodes uses the $d_{31}$ mode. This harvester can also use for other piezoelectric applications. The direction of the applied stress/strain is perpendicular to the induced electric field in this mode. Therefore, the induced voltage of the curve shaped piezoelectric generator can be calculated by using Equation (1).

Figures 10 and 11 shows the structure and working mechanism of the curved piezoelectric generator, where different stages of loading are shown: (a) initial state; (b, c) charge distribution during pressing; (d, e) charge distribution during force release; (f) three-dimensional schematic view of the curved piezoelectric harvester and wire connection of strained piezoelectric generator using high switching full wave rectifier.

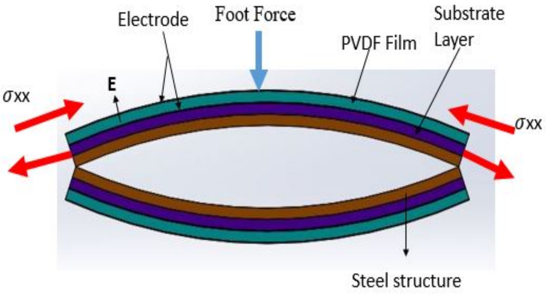


**Fig.10.** Model of curved structure.

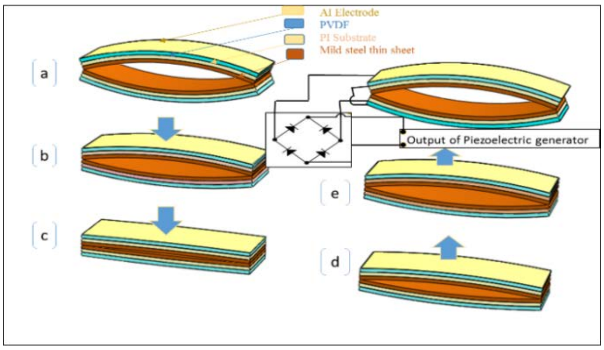


**Fig.11.** Work mechanism of curved energy harvester.

The curved shaped PI substrate structure of the curved piezoelectric power generator has two important roles. First, it effectively acts as a passive layer, when is subjected to the vertical force of the human. Since the PVDF film is very thin, it is unable to get the appropriate neutral plane of structure of piezoelectric generator and it also has a low Young's modulus. Therefore, PI substrate and steel substrate of the piezoelectric energy harvester should be appropriate thick to shift the neutral plane of the structure out of the piezoelectric PVDF film layer. On contrary, if the thickness of the piezoelectric PVDF film layer is very thick then the structure of energy harvester becomes more rigid, and subsequently it requires more force to generate the electric power. Secondly, the PI substrate also acts as an active layer that recovers the deformed piezoelectric PVDF film layer back into its original shape, like a leaf spring in a commercial automobile.

This harvester design also allows that the piezoelectric PVDF film is subjected to only tensile or compressive stress during the complete testing (pressing and releasing of human foot force). Because of this reason, the curved piezoelectric energy generator enhances the output power. This is because the proper thickness of the substrate layer makes the neutral plane shift from PVDF to its inside.

**Mathematical modeling of curved piezoelectric harvester.** When the piezoelectric energy harvesting device is pressed by external force in the middle of the device, the PVDF and substrate are subjected to compressive and tensile stresses, respectively, and voltage in 31 mode is defined as [23]

$$V_{31} = \sigma_{xx} g_{31} t\,, \qquad g_{31} = \frac{d_{31}}{\varepsilon_r \varepsilon^T}\,, \tag{7}$$

where, $t$ is the piezoelectric PVDF film thickness, $g_{31}$ is the piezoelectric voltage coefficient, $d_{31}$ is the module of piezoelectric material and $\varepsilon_r$ is the relative permittivity of PVDF.

The electric charge, induced on the surface of PVDF film by $d_{31}$ mode is given as

$$Q = d_{31} C_{11}^{E} \int_A S_1 dA\,, \tag{8}$$

where $A$ is the electrode area and $C_{11}^{E}$ is the stiffness matrix of component. The charge, produced in piezoelectric generator, is a function of strain, induced in the generator. For an impact type piezoelectric energy generator, the quasi-static analysis gives better result. Therefore, charge equation of curved piezoelectric generator is given as

$$Q = b d_{31} C_{11}^{E} \left( \frac{t + t_1 + t_2}{3} \right) \int_0^l \frac{\partial^2 w}{\partial x^2} dx\,, \tag{9}$$

where $b$ is the width of energy harvesting device and $w$ is the $z$-components of displacement vector at a point on the neutral surface.

Table 2 presents design parameters of curved piezoelectric energy harvester.

Table 2. Design Parameters of curved piezoelectric energy harvester.

| Parameter | Description | Value |
|---|---|---|
| $t$ | PVDF film thickness | 28 µm |
| $t_1$ | Thickness of PI substrate layer | 0.25 mm |
| $t_2$ | Thickness of steel plate | 0.15 mm |
| $w$ | Displacement | 10 mm |
| $b$ | Width of harvester device | 22 mm |
| $L$ | Length of harvester device | 72 mm |

**Fabricated model of energy harvester.** Figure 12 shows a curved piezoelectric energy harvester, which is placed under the heel in the shoe/saddle. This harvester has two PVDF films, connected in series. The electrodes of the piezoelectric films are connected to power extraction circuit. Readings shows in the digital storage oscilloscope (Fig. 13).

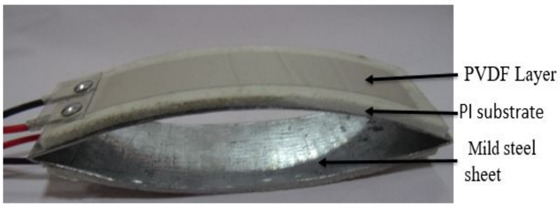


**Fig. 12.** Experimental model.

**Fig. 13.** Experimental setup.

**Experimental results.** In experiment, the harvester is appropriately placed in the shoe/sandal and the setup is worn on foot of a person with weight of 60 kgF. The person is then walks with the speed of approximately 2 steps/s.

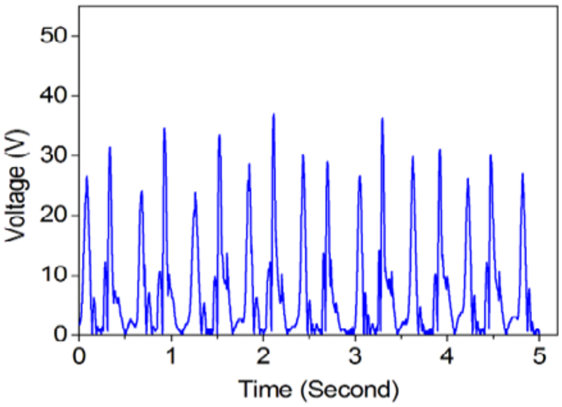


**Fig. 14.** Rectified voltage.

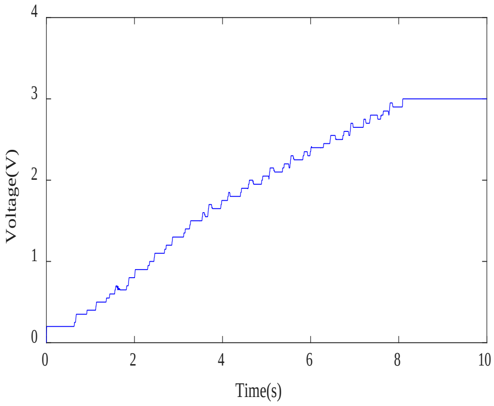


**Fig. 15.** Capacitor charging voltage.

Figure 14 shows the voltage across the 10 µF storage capacitor. The capacitor will be fully charge after 15 steps and it induces 3V DC output voltage (see Fig. 15).

## 4. Combination of both energy harvesters

While walking, the heel part of foot lands with much higher impact force. So in order to absorb this force effectively, the oval-shaped harvester was deployed as its structure can withstand wide range of deflection (see Fig. 16). Hence, the rapid deflection in the piezo-material resulted in high peaks of output voltage as apparent in Fig. 17. On the contrary, the forefoot is a flexible part, which experiences gradual load while walking. This makes it suitable for low deflection applications. Moreover, the sandwich type harvester had been precisely designed to produce higher strain in PVDF film with low deflection in its structure. Therefore, it was placed under the forefoot for energy harvesting.

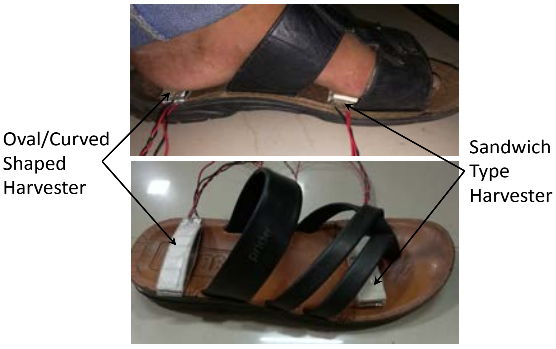


**Fig. 16.** Combination of both energy harvesters.

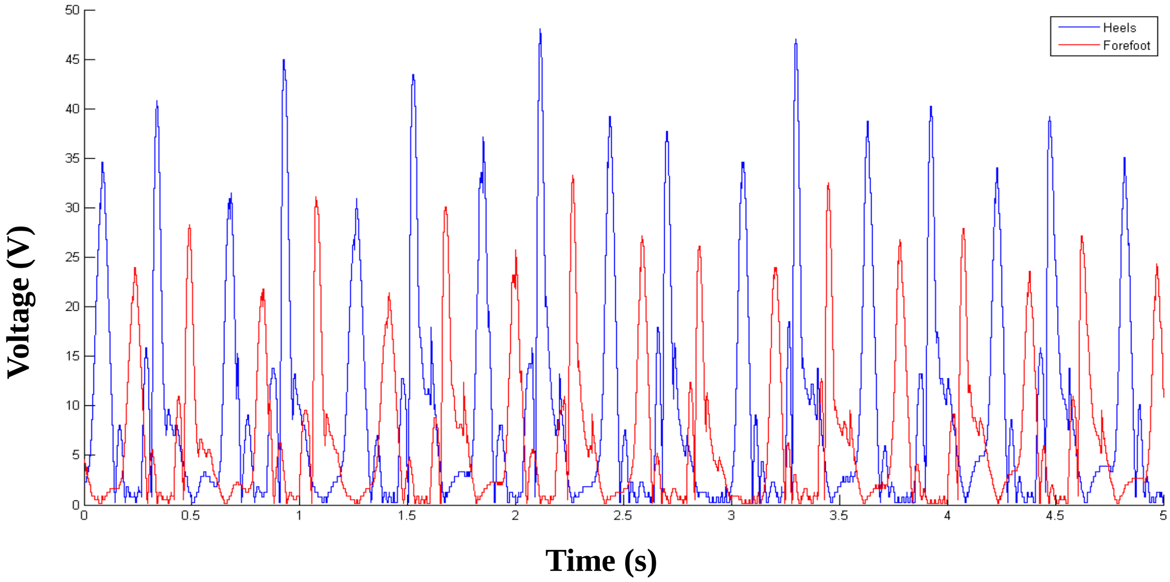


**Fig. 17.** Integrated Rectified voltage of combined energy harvester.

Firstly, the heel of foot makes contacts with ground and foot force gradually increases on the curved shaped structure. As steps progresses, the active force acting on this harvester decreases and shifts to the sandwiched type harvester placed under the fore-foot. This causes decay in voltage across the former harvester and increase in voltage across the latter.

## 5. Conclusions

The energy harvester, which is placed under the ball of foot, the rectified output voltage is obtained as 21 V and voltage across the 10 µF capacitor is obtained as 2.5 V. The output voltage across the capacitor is used to calculate the energy generation and generated output power is 3.9 µW. The energy harvester, which is placed under the heel of the foot, the rectified output voltage is obtained as 30 V. Output voltage across the 10 µF capacitor is obtained as 3 V and generated output power was 5.625 µW. The integrated average voltage output of the design is equal to 6.5 V. Subsequently, the average power output obtained was 9.625 µW.

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