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Piezoelectric energy harvester converting wind aerodynamic energy into electrical energy for microelectronic application

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Abstract

Piezoelectric Energy Harvesting Systems play a vital role in energizing microelectronic devices with the low-frequency operation. Here, a novel piezoelectric energy harvesting device has been developed for low power electronic devices. The developed Piezoelectric Energy Harvesting Systems consists of a cantilever with poles projecting outwards and the cantilevers one end is connected to the wind-catcher, and another end is connected to the torsional spring. The developed Piezoelectric Energy Harvesting Systems signifies its application in energizing microelectronic devices. The cantilever is placed inwards to the piezoelectric crystal stack. When the wind strikes, a vortex is created in the windcatcher, which oscillates the cantilever and generates stress in the piezoelectric crystal stack to develop electric energy. The output voltage obtained from the Piezoelectric Energy Harvesting Systems does not affect any input frequency of the piezoelectric crystal. The result obtained shows that the developed Piezoelectric Energy Harvesting Systems generates 120–200 eV with 2.9×10^{16}–4.84×10^{16} Hz frequency considering an elementary charge unit as 40 for a variable wind flow of 4–9 m/s. This research aims to develop an efficient wind-based Piezoelectric Energy Harvesting Systems for low powered microelectronic devices.

1 | INTRODUCTION

The recent advancement of semiconductor engineering has led to developing microelectronic devices. The developed electronic devices play a significant role in the modern world in the fields of health monitoring, wireless communication, remote sensing, household appliances, agriculture, automobile industries, etc. [1]. The primary challenges that the semiconductor sector faces are powering such a microelectronic device for a long-time usage [2]. The microelectronic devices are powered either by batteries or regenerative energy sources.

Polypropylene Ni-metal hydride battery, Lithium-ion micro battery, and Silicon nitride ceramic battery have been proposed to power the microelectronic devices [3–5]. The proposed batteries are very much enhanced in energy density, efficiency, and their smaller size. They are also able to operate for a more extended period of time. Nevertheless, in some applications, the device has been deployed in the human body or unreachable remote location. In such cases, replacement of battery can be challenging or even practically impossible. To resolve such issues in replacement, and power up such electronic devices, regenerative energy sources have been used [6]. The regenerative energy source uses the movement of living organisms, mechanical vibration, solar energy, wind energy, and temperature to generate ambient energy to power up the microelectronic devices [7].

The usage of Piezoelectric Energy Harvesting Systems (PEHS) is a newly emerging research area associated with the regeneration resources. In general, PEHS uses mechanical stress or strain to generate electrical energy. Therefore, a vibration source is additionally required for PEHS to generate vibration. Some approaches have focused on vibration sources for PEHS from natural energy such as solar, wind, ocean, and external motion in the literature [8–10]. A raindrop based PEHS has been developed [8]. This approach uses raindrops to generate vibration for the PEHS. However, according to the monsoon season earth doesn't get rainfall all through the year. Therefore, this approach has limitations in its usage. PEHS based on the vibration of the vehicle in public roadways has been proposed [9]. The proposed approach has an efficient way of generating stress and strain.

Nevertheless, the thin film gets torn and damages quickly due to the striking an object by the vehicle. Memory alloy based PEHS has been proposed in [10]. The required vibration for the PEHS has been produced by heating and cooling the memory alloy. Furthermore, wind energy is another valuable natural resource used as a source of vibration in PEHS [11]. A laminar wind tunnel with the wind as a source of vibration for PEHS has been studied [12]. In another approach, a bioinspired piezo-leaf architecture is fabricated using thin-film piezoelectric cell has been studied [13]. In [14], the authors proposed a wind-based PEHS which uses bimorph-piezoelectric mounted on a windmill. The above work uses wind energy to develop mechanical vibration through unsteady pressure of the vortex created by the wind flow. The research conducted uses thin-film piezoelectric cells and they are usually capable of generating a very less power in mW. In another approach, an energy harvester comprising a cantilever attached to piezoelectric patches is proposed [15]. This approach uses the crosswind field to generate 2W power and is possibly achieved when the resonant frequency of the cantilever harvester is close to the vortex shedding frequency. The article has concluded that critical and enhanced piezoelectric crystal is required for efficient PEHS [16–19]. Several researchers have applied piezoelectric energy harvesting systems. By enhancing the piezoelectric crystal, a new power od 30–50 mW can be achieved higher than the previous work.

In this literature, an experimental study has been carried out to evaluate the efficiency of the proposed PEHS. The proposed approach uses wind vortex phenomena to generate vibration for the piezoelectric crystal. The advantage of the proposed PEHS is that it consists of a wind catcher that is able to catch the wind in all directions. Furthermore, it is designed in such a way that it comes back to the normal position with the help of a torsional spring when there is no wind flow. Therefore, damage of the piezoelectric crystal can be avoided. The cantilever is placed inwards to the piezoelectric crystal stack. When the wind strikes, a vortex is created in the windcatcher, which oscillates the cantilever and generates stress in the piezoelectric crystal stack to develop electric energy. The piezoelectric used in the proposed harvesting system is made of thiol capped ZnO based Polyvinyl di-Fluoride (PVDF) piezoelectric crystal. Therefore, the PVDF polymer has higher efficiency than the conventionally used Zirconate Titanate (PZT), Macro Fibre Composites (MFC), and Quick Pack (QP) material. The output voltage obtained from the PEHS does not affect any input frequency of the piezoelectric crystal. The result obtained shows that the developed PEHS generates 120–200 eV with

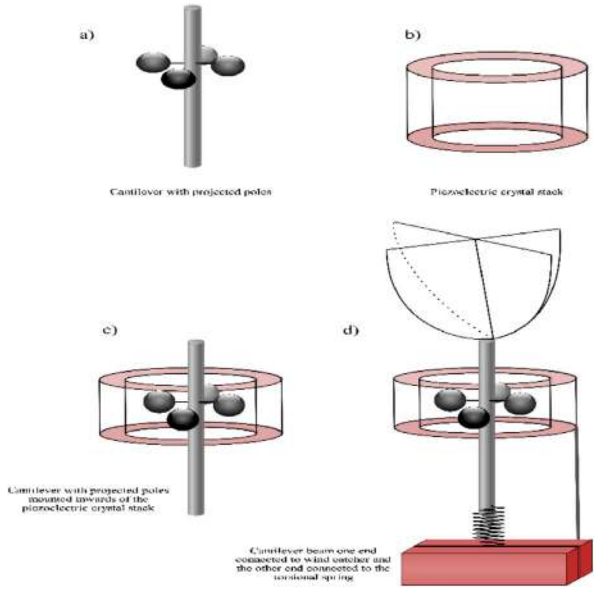

FIGURE 1 Modelling of the proposed PEHS, (a) cantilever with projected poles, (b) piezoelectric crystal stack, (c) piezoelectric crystal stack fixed to cantilever, (d) complete setup of proposed PEHS

2.9 × 1016–4.84 × 1016 Hz frequency considering an elementary charge unit as 40 for a variable wind flow of 4–9 m/s. This research facilitates to develop an efficient wind-based PEHS for low powered microelectronic devices.

2 | MODELLING AND FUNCTION OF THE PROPOSED PIEZOELECTRIC ENERGY HARVESTING SYSTEM FOR WIND-INDUCED VIBRATION

The method of harvesting electric energy from mechanical vibration is known as the piezoelectric effect. Conversely, it could be seen as an ability of piezoelectric crystals to generate an electric charge in response to applied mechanical stress. In this study, wind energy is set to apply mechanical stress to the piezoelectric crystals. The amount of energy obtained using this effect is known as piezoelectricity. The developed PEHS model consists of a wind catcher made up of PVC material. The windcatcher is designed in such a way that it is possible to capture wind from all directions [20–22]. The wind capture is mounted over a cantilever. The cantilever is made of an aluminium rod whose length L is 1.2 m and a diameter of 1 cm. The cantilever one end is connected to windcatcher, and another end is connected to torsional spring. The cantilever consists of pole projecting outward, whose pole is made of ethylene propylene diene monomer rubber as shown in Figure 1(a). Figure 1(b) shows the piezoelectric crystal stack THIOL capped Zinc Oxide based Polyvinylidene Fluoride (THIOL-ZnO+PVDF). The THIOL-ZnO+PVDF is fabricated based on [23–25]. The material properties of the developed THIOL+ZnO+PVDF based piezo electric crystal is listed in Table 1. The dimensions of Thiol+PVDF is volume 2.34×10^{-3}, lateral

TABLE 1 Material properties of thiol capped PVDF

Standard properties	Thiol+PVDF
Melting point in°C	154–184
Specific gravity in g/cm^3)	1.75–1.80
Tensile Strength at environment condition	36–56
Elongation at environment condition	25–500
Izod impact strength at environment condition	160–530
Coefficient of thermal expansion	~10^{-4}
Dielectric constant,(1 kHz)	7.5–13.2
Dielectric strength, (kV/mm)	260–950
Dissipation factor, (1 kHz)	0.0163–0.019

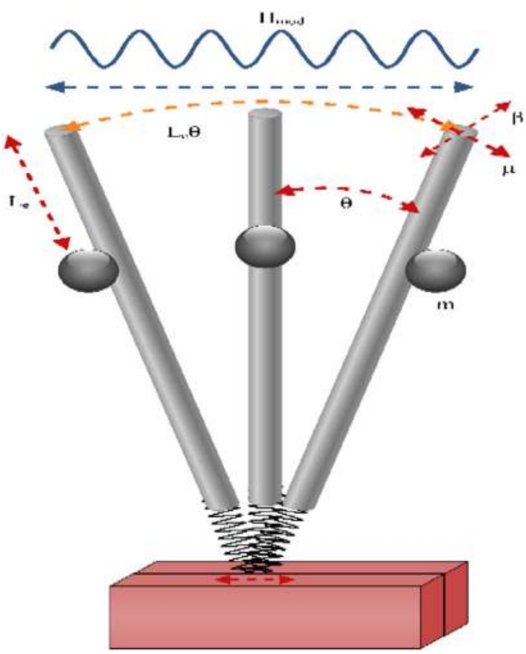

FIGURE 2 The function of the cantilever for wind strike

area 0.47, and surface area 0.50; the dimension of PVDF is volume 2.36×10^{-3}, lateral area 0.469, and surface area 0.501; and the dimension of PZT is volume 2.32×10^{-3}, lateral area 0.469, and surface area 0.50, the values are calculated in m scale.

The piezoelectric stack is enclosed and covered by six-inch plastic material and fixed outer to the cantilever as shown in Figure 1(c). The cantilever is mounted on torsional spring, and the latter is fitted to the concrete support as shown in Figure 1(d). The proposed PEHS operates based on the wind vortex created by the flow of wind. The wind may strike the cantilever attached to the windcatcher. Figure 2 shows the function of the cantilever for wind strike. When the wind strikes the cantilever beam, the projected metal ball strikes the piezoelectric crystal to generate energy. The cantilever oscillates back and forth and forms a hyperbolic curve with the noticeable structures that a tangent to the end of the cantilever always intersects its point along the middle axis. The corresponding Lagrangian equation is given as [26–30] shown below:

$$L = \frac{1}{2}m(L_e\theta)^2 - \left\{\frac{1}{2}k(L_e\theta)^2 - \mu B\cos(\theta-\beta) + k_u V \sin^2\beta\right\} \quad (1)$$

where m is the mass of poles in cantilever beam, V is the volume of the particle, k is the constant of the cantilever, L_e is the length of the cantilever, μ is the angular momentum. The Lagrangian equation consists of two variables θ and β, and the corresponding equation for the two variables is given as:

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\beta}} = \frac{\partial L}{\partial \beta} = \mu B\sin(\theta-\beta) - 2k_u V\sin\beta\cos\beta \quad (2)$$

$$\beta = \frac{B\theta}{B+H_k} \quad (3)$$

$$H_k = \frac{2k_u V}{\mu} \quad (4)$$

Let, θ be the angle, and as the function of the Lagrangian equation, it is given as follows:

$$\theta - \beta = \frac{\theta H_k}{B+H_k} \quad (5)$$

then,

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}} = \frac{\partial L}{\partial \theta} \quad (6)$$

Therefore,

$$mL_e^2\ddot{\theta} = -kL_e^2\theta - \mu B\sin\left(\frac{\theta H_k}{B+H_k}\right)\left(\frac{H_k}{B+H_k}\right) - 2k_u V\sin\left(\frac{\theta B}{B+H_k}\right)\cos\left(\frac{\theta B}{B+H_k}\right)\left(\frac{\beta}{B+H_k}\right) \quad (7)$$

$$mL_e^2\ddot{\theta} = -kL_e^2\theta - \mu B\theta\left(\frac{H_k}{B+H_k}\right)^2 - \mu H_k\theta\left(\frac{B}{B+H_k}\right) \quad (8)$$

$$mL_e^2\theta = \ddot{\theta} + \theta\left(\frac{kL_e^2 + \frac{\mu BH_k}{B+H_k}}{mL_e^2}\right) \quad (9)$$

$$mL_e^2\theta = \ddot{\theta} + \theta\left(\omega_0^2 + \frac{kL_e^2 + \frac{\mu BH_k}{B+H_k}}{mL_e^2}\right) = 0 \quad (10)$$

where,

$$\omega^2 = \left(\omega_0^2 + \frac{kL_e^2 + \frac{\mu BH_k}{B+H_k}}{mL_e^2} \right) \tag{11}$$

The solution of the differential equation is $\theta(t) = C_1 \cos \omega t + C_2 \sin \omega t$, where C_1 and C_2 are the coefficients determined by the initial condition. The binomial equation is given as in [29]; see below:

$$\frac{\omega - \omega_0}{\omega_0} = \frac{\Delta\omega}{\omega_0} = \frac{\mu HH_k}{2kL_e^2(H + H_k)} \tag{12}$$

From the above equation, the voltage generated in the piezoelectric stack is given as:

$$V_{PEHS} = \frac{e31B(H + H_k)}{2C_v} \int_L^{L+\alpha} \frac{d^2\omega}{dx} dx \tag{13}$$

where C_v is the electric capacity of the piezoelectric stack, $e31$ is the electric constant and $\alpha = 8$ when the cantilever gets vibrated (i.e.) α orientation angle of the beam measured for the study. The voltage generated in the developed model is given as:

$$V_{g,PEHS} = \frac{e31B(H + H_k)\rho Av^2 B\mu L}{4C_v} \times Sin\omega t \times \sum_{n=1}^{\infty} \frac{C_n}{B_n \Delta\omega^2} \int_L^{L+\alpha} \frac{d^2\omega}{dx} dx \tag{14}$$

Here, the charge is generated as given below:

$$Q_g(t) = C_v \times V_{g,PEHS}(t) \tag{15}$$

The charge is generated when the projected poles squeeze the piezoelectric crystal and cantilever moves to its stable position when there is no wind flow employing torsional spring. Based on the load, the output power varies when analysed using the load test. The real power generated by the developed PEHS can be calculated through root mean square (RMS) for a time period T. The total power generated by the proposed PEHS for the period of 0–T is given as:

$$P_{(RMS)} = \sqrt{\frac{1}{T} \int_0^T [p(t)]^2 dt} \tag{16}$$

Where, $p(t)$ is the extracted power for the piezoelectric stack mounted to the cantilever at time $0 \leq t \leq T$, when $p(t) = \frac{dQ_g(t) \times V_{g,PEHS}}{dt}$.

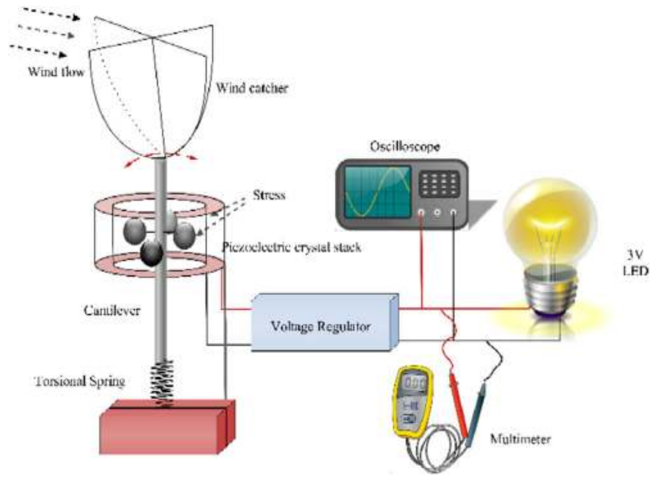

FIGURE 3 Architecture diagram of the proposed PEHS

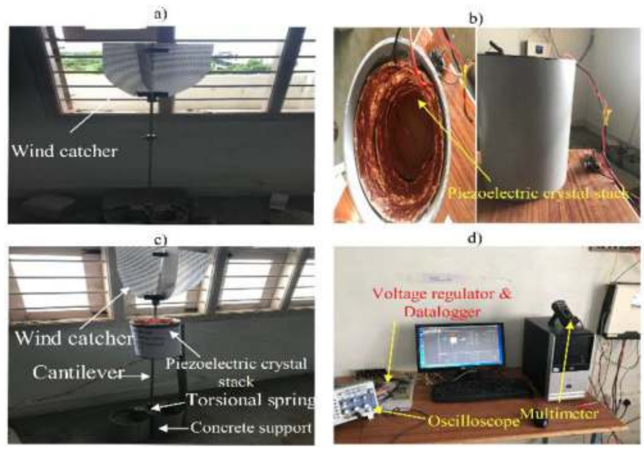

FIGURE 4 Experimental setup of the fabricated PEHS

3 | RESULTS AND DISCUSSION

The architecture of the proposed PEHS is shown in Figure 3. In the architecture, the piezoelectric crystal stack is connected to the voltage regulator. The function of the voltage regulator is to maintain a constant output voltage. The voltage regulator uses 7806 IC (Integrated Circuit) voltage regulator with two 0.22 μF capacitors connected parallel; for more details on its function see: [31]. The output of the voltage regulator is connected to the 3 V LED load. To measure the voltage and current flowing through the circuit a multimeter is connected in series to measure current in A and connected in parallel to measure voltage in volts. Further, to analyse the load characteristics, the 3 V LED load is replaced by load resistors of 10, 33, 57, 70, 100, 120, 160, 220, 240, 300, and 360 kΩ, respectively. The voltage and current are measured using the multimeter and corresponding power is calculated.

The experimental setup of the proposed wind vortex phenomena based PEHS is shown in Figure 4. Figure 4(a) shows

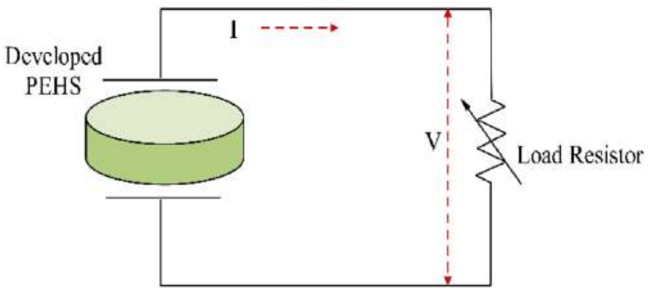

FIGURE 5 Circuit diagram from the load test

the photograph of the windcatcher, which is attached to the cantilever. The cantilever has a pole projection, as shown in Figure 4(a) and its bottom is grounded to a concrete bed through a torsional spring. Figure 4(b) shows the thiol capped PVDF piezoelectric stack. The fabricated PEHS consists of 3 stacks, which are connected in series to form a complete piezoelectric stack pack. The fabricated stacks are kept in a PVC holder so that the stacks get protected from the outer environment, as shown in Figure 4(b). Figure 4(c) shows the complete setup of the fabricated wind vortex based PEHS. Figure 4(d) shows the measuring instruments of the fabricated PEHS setup.

To evaluate the behaviour of the fabricated PEHS, a load test is conducted under peak load condition. The circuit used for analysing the load test is shown in Figure 5. The PEHS is connected to the load resistors of 10, 33, 57, 70, 100, 120, 160, 220, 240, 300, and 360 kΩ, respectively. The voltage and current are measured using the multimeter, and corresponding power is calculated.

3.1 | Experimental validation

To validate the performance of the proposed wind vortex phenomena based PEHS, the developed PEHS has been subject to analysis under three cases: (a) Computational Fluid Dynamic (CFD) analysis for the windcatcher, (b) output power analysis for the wind speed of 5–10 m/s under reasonable the condition with different piezoelectric crystal stacks PVDF and PZT, and (c) behaviour of proposed PEHS under loaded condition.

Initially, the developed windcatcher is validated to prove the phenomena of the vortex. The developed windcatcher is modelled in 3D and has been subjected to CFD analysis. Figure 6 shows the results obtained for the CFD analysis for the developed windcatcher. From Figure 6(a), it can be observed that the wind is allowed to flow from east to west. It can be noted that the windcatcher blocks the wind flow and creates vortex at the right of the 3D image viewed in the top angle. Figure 6(b) shows the CFD analysis for the developed windcatcher for 3D view. In this analysis, wind flow is set to flow from west to east, and it can be noted that a high-pressure vortex is created in the windcatcher. From this analysis, it can be understood that the developed windcatcher for the proposed PEHS can catch the wind flow and create a vortex in its blades.

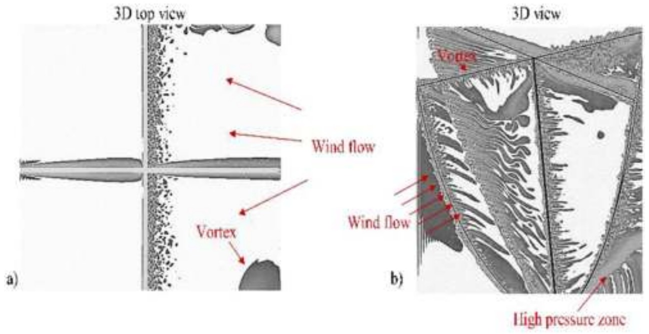

FIGURE 6 Computational fluid dynamic (CFD) analysis of the windcatcher, (a) vortex shedding at the windcatcher 2D top view, and (b) vortex shedding at the windcatcher 3D view

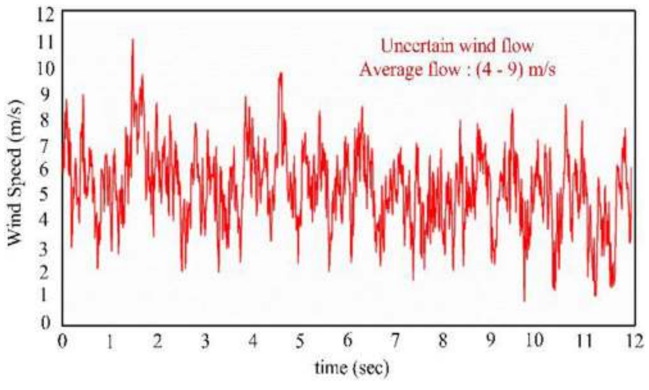

FIGURE 7 Wind speed measured in the study

In further analysis, the proposed PEHS is exposed to the wind flow of 5–10 m/s. The real-time wind speed measured has been depicted in Figure 7. The wind flow is uncertain and varies between 4 m/s to 12 m/s at an average speed of 9 m/s. Figure 8 shows the output voltage measured for the proposed PEHS. From the figure, it can be observed that from 0 to 1 s the windcatcher caught a mild wind flow, hence with slight vibration, the PEHS has not produced a small voltage output. From 1 to 2 s, the windcatcher has experienced strong wind flow; therefore, due to the vibration of wind flow, the PEHS has generated an

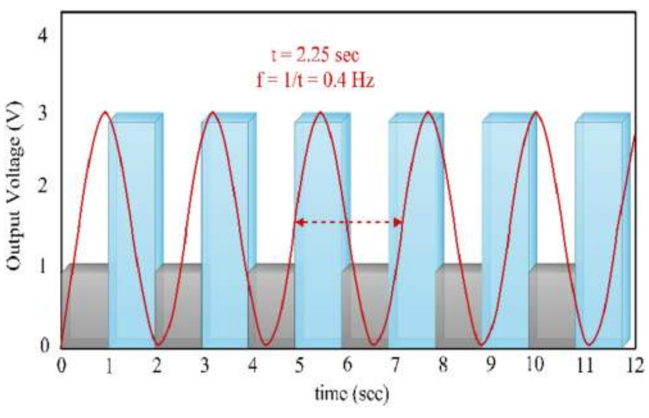

FIGURE 8 Output voltage observed in the developed PEHS

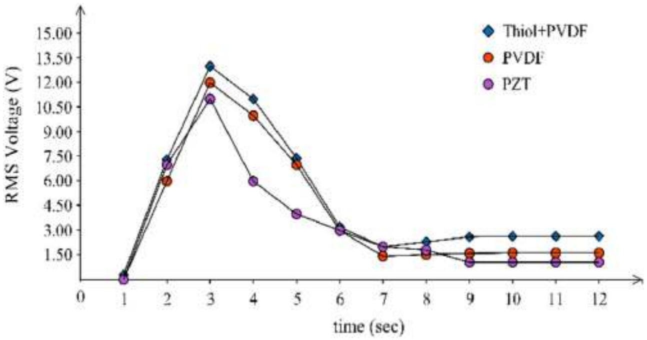

FIGURE 9 RMS voltage of the studied PEHS

output voltage of 3 V for with a frequency of 0.4 Hz. The RMS voltage obtained for the PEHS is depicted in Figure 9. From the figure, it can be observed that it delivers an average RMS voltage of 3.2 V. The PVDF based PEHS delivers an average RMS voltage of 2.67 V and PZT delivers an RMS voltage of 1.97 V.

The corresponding peak power obtained for developed PEHS, PVDF and PZT is depicted in Figure 10. The peak voltage has been analysed based on different wind flow and frequency. Figure 10(a) depicts the peak voltage obtained for high wind flow of 9–12 m/s. The maximum peak voltage occurs as 4000 cycles and it has been observed that developed PEHS with thiol capped PVDF has a higher peak value of 4 V. Figure 10(b) depicts the peak voltage obtained for wind speed 6–8 m/s. It has been observed that a peak voltage of 3.2, 2.8, and 2 V at 4000 to 5000 cycle for developed PEHS, PVDF, and PZT based PEHS, respectively. Figure 10(c) depicts the peak voltage obtained for wind speed 4–6 m/s.

It has been observed that a peak voltage of 1.83, 1.4, and 1.39 V at 4000 cycles for developed PEHS, PVDF, and PZT based PEHS, respectively. Figure 10(c) depicts the peak voltage obtained for very-low wind speed < 3 m/s. The probability of generating a voltage at this wind flow is less. It has been observed that a peak voltage of 0.5, 0.31, and 0.3 V at 4000 cycles for developed PEHS, PVDF, and PZT based PEHS, respectively

The proposed PEHS is subjected to load test, and the connections are given as per the circuit diagram is shown in Figure 5. In this analysis, the load resistors of different values of 10, 33, 57, 70, 100, 120, 160, 220, 240, 300, and 360 kΩ are used as the load for the PEHS. The corresponding output power is depicted in Figure 11. From the figure, it can be observed that with an increase in load, the power increases. It can be seen that the power increases linearly with an increase in load. The output power does not always increase; it gets decreases when the load is increased after a certain point.

Furthermore, a comparative analysis has been carried out in [15, 19], and corresponding analysis results are shown in Table 2. In this analysis, only PEHS with single stack has been

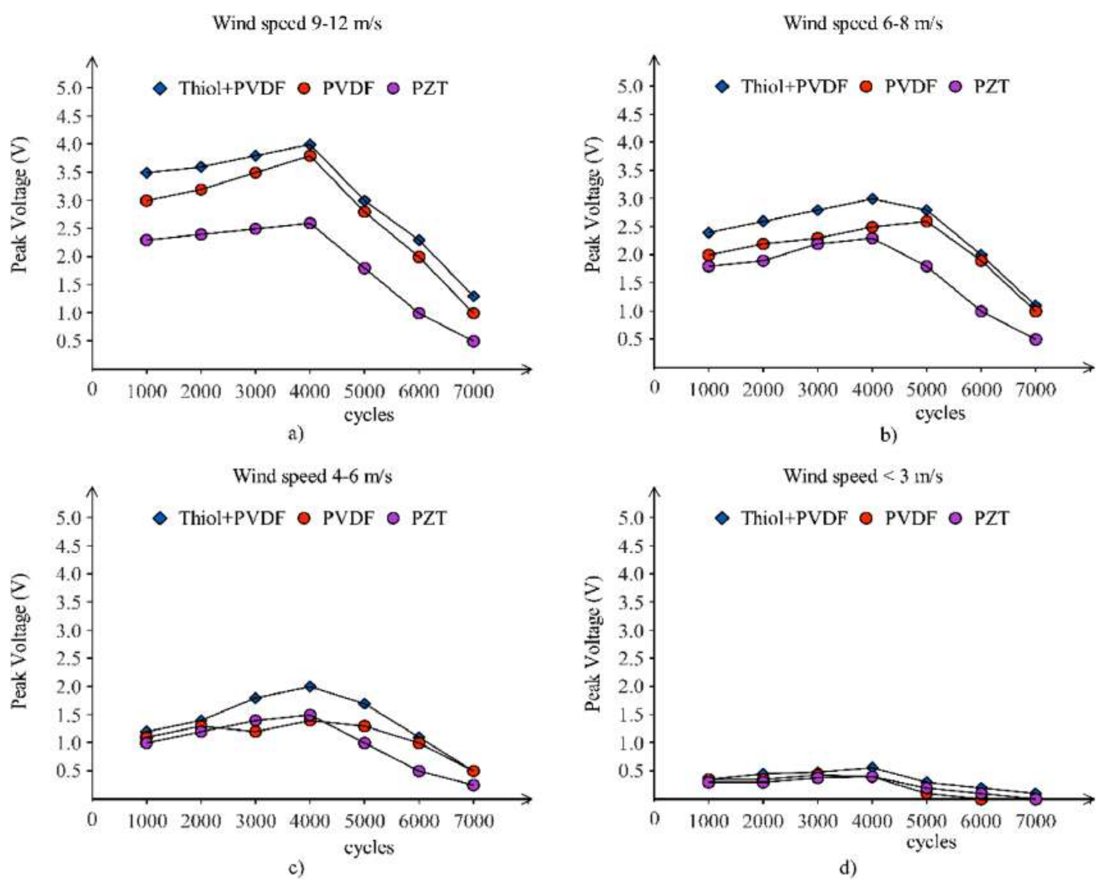

FIGURE 10 Peak voltage observed in the studied PEHS

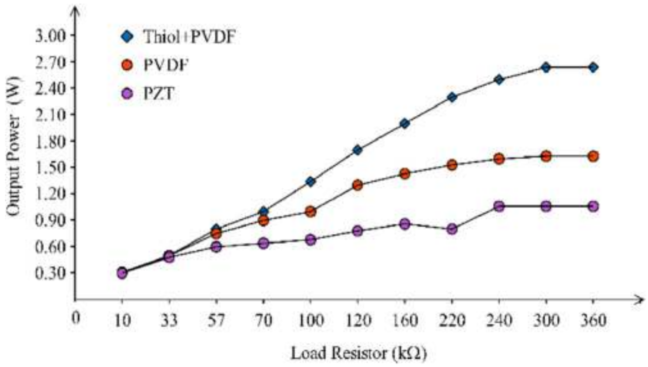

FIGURE 11 Output power observed in the studied PEHS

TABLE 2 Comparative analysis of different wind-based PEHS

The piezoelectric energy harvesting system	Piezoelectric material	Max. output power [W]
Proposed PEHS	Thiol capped PVDF	2.6
PEHS with PVDF	PVDF	1.63
PEHS with PZT	PZT	1.06

compared with the other works. From the table, it can be seen that the proposed PEHS generates a 120–200 eV with 2.9 × 1016–4.84 × 1016 Hz frequency considering the elementary charge unit as 40 with an output power of 2.6 W for 240 kΩ loads. Thus, the results show the effectiveness of our novel wind-based PEHS scheme, which can generate electric power for the microelectronic devices.

4 | CONCLUSION

Piezoelectric energy harvesting is a promising field of generating clean energy from the excitation of mechanical vibration for energizing the microelectronic appliances. In this paper, a novel wind excitation based piezoelectric energy harvesting system has been developed. The developed system is evaluated under different studies, and the following observation is noted:

1. Developed piezoelectric energy harvesting system has the capability to generate vibration under all sort of wind direction by creating a vortex in the windcatcher and able to generate electric energy effectively at the speed of 4–11 m/s.
2. The thiol capped PVDF piezoelectric crystal stack generates 120–200 eV with 2.9 × 1016–4.84 × 1016 Hz frequency considering an elementary charge unit as 40.
3. The projection in the cantilever can be adjusted following the wind speed to avoid the striking of the piezoelectric crystal.

The result obtained for the developed PEHS is quite standard. The PEHS can generate 3 V with 0.4 Hz frequency for an uncertain wind flow of 4–11 m/s. It is also observed that it can generate an RMS voltage of 3.2 V with a peak power of 4 V at wind speed 9–11 m/s. Further, it is observed from the load test that the developed PEHS can generate an output power of 2.6 W, which is more enough to power the microelectronic devices and wireless sensor devices. The output shows the success of the developed PEHS and the novel wind-based PEHS provides efficient energy and can be utilized for energizing microelectronic appliances.

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