**International Journal of Electrical and Computer Engineering (IJECE)**
Vol. 12, No. 6, December 2022, pp. 5861~5871
ISSN: 2088-8708, DOI: 10.11591/ijece.v12i6.pp5861-5871 

# Simulation and performance analysis of self-powered piezoelectric energy harvesting system for low power applications

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**Article Info**

***Article history:***

Received Sep 13, 2021
Revised Jun 20, 2022
Accepted Jul 17, 2022

***Keywords:***

Battery-less
Energy harvesting
Maximum power point tracking
Modeling
Piezoelectric sensors
Rectifier
Self-power

**ABSTRACT**

Energy harvesting is a process of extracting energy from surrounding environments. The extracted energy is stored in the supply power for various applications like wearable, wireless sensor, and internet of thing (IoT) applications. The electricity generation using conventional approaches is very costly and causes more pollution in the environmental surroundings. In this manuscript, an energy-efficient, self-powered battery-less piezoelectric-based energy harvester (PE-EH) system is modeled using maximum power point tracking (MPPT) module. The MPPT is used to track the optimal voltage generated by the piezoelectric (PE) sensor and stored across the capacitor. The proposed PE system is self-operated without additional microarchitecture to harvest the Power. The experimental simulation results for the overall PE-EH systems are analyzed for different frequency ranges with variable input source vibrations. The optimal voltage storage across the storing capacitor varies from 1.12 to 1.6 V. The PE-EH system can harvest power up to 86 µW without using any voltage source and is suitable for low-power applications. The proposed PE-EH module is compared with the existing similar EH system with better improvement in harvested power.



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## 1. INTRODUCTION

The energy harvester (EH) extracts a small amount of energy from ambient vibrations. The EH module provides sufficient power to charge electrical storage devices like storage capacitors or rechargeable batteries. In recent times, the EH module provides power to portable electronic devices like mobile phones, medical equipment, and wireless sensor nodes (WSN) at different interval times. Energy harvesting is achieved from natural resources and biological resources [1]. Power harvester develops battery-less devices and operates based on self-power operation. The power harvester utilizes the energy from its surrounding environment and generates valuable energy. Nowadays, researchers are more focused on battery-replacement systems using feasible energy resources because of more power consumption of sensor nodes and the size of electronic devices [2]. The energy resources are available freely and can be used for power applications. The energy sources are thermal, chemical, mechanical, electromagnetic, human-body, radioisotope, and biological energies. For example, the human body can generate energy by performing some operations like walking, jogging, heartbeat, and blood pressure [3]. There are many mechanisms available to convert mechanical to electric energy, which include, piezoelectric (PE), electromagnetic (EM), and electrostatic

(ES). Using an energy harvester, these three approaches use vibration (mechanical) energy to electrical energy. The PE generator uses PE material to convert the vibration to electrical energy. The EM generator uses the magnet that oscillates in a coil, which results in current flowing in the coil using faradays theory. The ES harvester has two plates separated by a dielectric film that vibrates reasonably to each other and acts as a variable capacitor. In addition to that, other energy harvesters like thermo-electric, photovoltaic, radio-frequency-based EH systems are available to generate electrical energy [4]–[6]. The PE-EH system is used in non-destructive testing (NDT) [7], interactive displays [8], WSN [9], and low-power ubiquitous applications [10] to harvest the power. The PE-EH system is does not require any voltage source, and it is difficult to integrate with any microsystem. The PE-EH system consumes little power per unit and is well suited to all power electronic applications, primarily low power applications.

The battery-less, self-powered piezoelectric-based energy harvesting system is modeled in this manuscript. The PE sensor voltage is disconnected periodically from the load applications, and it is difficult to track the optimal voltage and power in the EH system. So maximum power point tracking (MPPT) is introduced with a control mechanism to provide the necessary power to the system by holding ambient vibrations. The optimal voltage is used to track the vibrations and supply to the control mechanism to correct the voltage variations from the MPPT. The proposed system is energy-efficient and harvests a good amount of power using the MPPT method. The EH system stores an amount of optimal voltage across the capacitor and obtains better-harvested power. Section 2 elaborates on the proposed self-powered PE-based energy harvester system and its submodules in detail. The results and discussion for each sub-model and overall, PE-based EH system is analyzed in section 3. The conclusion of the proposed work with future scope is discussed in section 4.

The existing approaches of energy harvester systems using different ambient vibrations for various applications are discussed as below. Hu *et al.* [11] present the PE vibration EH system by improving the power extraction capability. The MPPT algorithm with the current control and predicting unit is incorporated to enhance the PE-EH system's power extract capability. The system obtains 6.6 V sensor voltage at 200 Hz and 198.5 µW of harvested power using the 0.18 complementary metal–oxide–semiconductor (CMOS) technology process. Jin *et al.* [12] designed high-performance EH devices using PE materials, investigated the PE properties, and fabricated lead-free PE materials. Johari and Rashid [13] describe the optimization process of PE transducer placement for EH in shoe insole. The tactile is used to select the different PE disk sizes and obtain the average output voltages. The output voltage for additional weight steps using the foot is discussed in detail. Othman *et al.* [14] present the modeling of the PE-EH system model embedded in a Soldier’s boot. The soldier's boot information acts as a mechanical load to the EH system, followed by the PE sensor. The sensor voltage was rectified to direct current (DC) and stored as an energy storage unit in a supercapacitor. The supercapacitor charges up to 5.5 V while walking for 1 hour, and it is sufficient to charge the soldier's boot.

Ruan *et al.* [15] discuss the energy-aware techniques for EH-powered wireless sensor nodes (WSN). The system uses an energy-aware interface (EAI) unit to rectify the mismatches through the energy process using a storage capacitor to WSNs. The WSN system is connected to the energy harvesting source via EAI and reduces the sleep current to 0.095 µA. The overall system obtains the 3.2 mW of power by PE-EH system by combining the WSN and EAI. Songsukthawan and Jettanasen [16] discuss the PE materials used to store and generate electrical energy. The work examines the PE effect and materials used for the experiments. The PE film is connected to nickel metal hydride (NiMH) battery model and analyzes the state of charge (SOC) for charging current and voltages. Oh *et al.* [17] present the PE-EH model's CMOS implementation for powering the wearable sensors. The full-wave rectifier is designed using two negative-MOS (NMOS) and positive-MOS (PMOS) transistors to reduce the wastage of power. The experimental results of the system achieve 0.52 V output voltage and 2.7 µW output power. Zhou *et al.* [18] present the PE-EH system using parallel synchronized switching harvesting on inductor (P-SSHI). The active rectifier is used with P-SSHI to reduce the circuit's voltage drop. The current work using an active rectifier consumes better output voltage and power than the conventional rectifiers.

Ma *et al.* [19] discuss the PE-EH module with simultaneous sensing and energy harvesting (SSEH) demonstration. The module includes a unique filtering technique to minimize the sensing distortion signal. The PE-EH Module consists of a sensor with a matching resistor and a bridge rectifier connected to the storing capacitor. The model is demonstrated for the subject walking scenario. Balguvhar and Bhalla [20] discuss the PE materials-based green energy harvesting system. Using a traditional rectifier circuit at a lower frequency, the EH is performed from bridge vibrations. The power obtained as 0.2 µW at 4 Hz with an output voltage of 4 V. Jayarathne *et al.* [21] present the vibration-based EH device using PE sensors. The lead zirconate titanate (PZT) based PE material is selected for modeling to identify the resonant frequency. The cantilever type configuration is chosen to model the PE-EH system. The average voltage of 3.65 V and

5.99 V is obtained by testing the prototype and theoretical calculations. Li *et al.* [22] discuss the PE-EH system with a parallel SSHI rectifier to achieve maximum energy extraction on a 180 nm CMOS process.

The MPPT module is integrated with the system to improve power and energy efficiency. Wang *et al.* [23] present the Buck converter model using multi-input synchronous electric charge extraction (SECE) for the PE-EH system. The work extracts the energy with the phase difference of zero to 2 $\pi$. The multi-input SECE uses the PE transducer module to perform the self-power operation. Xia *et al.* [24] present the hybrid rectifier module for the PE-EH system. The hybrid module includes a series of SSHI and SECE modules used for energy extraction. The hybrid approach obtains 0.28 mW power and 5.9 V of the output voltage. Wu *et al.* [25] present the two-directional EH module with a single PE film. The model predicts the force amplification ratio and achieves 286.70 kW/m in two directions. Kara *et al.* [26] discuss the Triboelectric EH system using a parallel-SSHI rectifier. The system delivers 722 μW of power to the load application in 4 ms.

## 2. PROPOSED ENERGY HARVESTING SYSTEM

The battery-less piezoelectric energy harvesting system is presented in this section. The energy harvester system provides solutions to resolving ambient vibrations issues to generate electricity. The proposed method works without any chemical battery and provides electricity using ambient vibrations. The overall energy harvesting system is explained in the below subsections.

### 2.1. PE-based energy harvesting system

The proposed energy harvester (EH) system mainly contains piezoelectric film, alternating current (AC) to DC rectifier, maximum power point tracking (MPPT) module, control unit, and DC to DC converter followed by load application. The PE-based energy harvester working based on ambient vibrations and MPPT is represented in Figure 1. The PE sensor provides a sensor output voltage to two MOSFETs $N_0$ and $P_0$. The MPPT module uses the MOSFETs $N_0$ and $P_0$ to track the maximum power point. The N-channel MOSFET ($N_0$) disconnects the MPPT occasionally from the PE sensor. The pulse generator provides pulses in regular intervals to the P-MOSFET followed by N-MOSFET. The N-MOSFET channel is periodically connected to the MPPT module. The optimal voltage is not constant, and it is not easy to supply directly to the load. So, the control module is used to maintain the supply power to the load applications with the help of MPPT. The DC-to-DC converter provides a small amount of power to the load regularly. The self-power is working in the system only when the components' power utilization is lesser than the optimal voltage ($V_s$) value. The control module mainly contains three comparators and a Schmitt trigger unit. The control module preserves the maximum voltage at the output point and provides the $V_s$ at PE-EH. The control module provides two output signals: control and enables (en). The control signal is used to operate the P-channel MOSFET ($P_1$) and enable signal to monitor the application functionary. The MOSFET $P_1$ is activated only when the control signal is low; otherwise, $P_1$ will be turned off. Most of the time, the MOSFET $P_1$ will be started to perform automatic functionality and track the load applications via DC-to-DC converter.

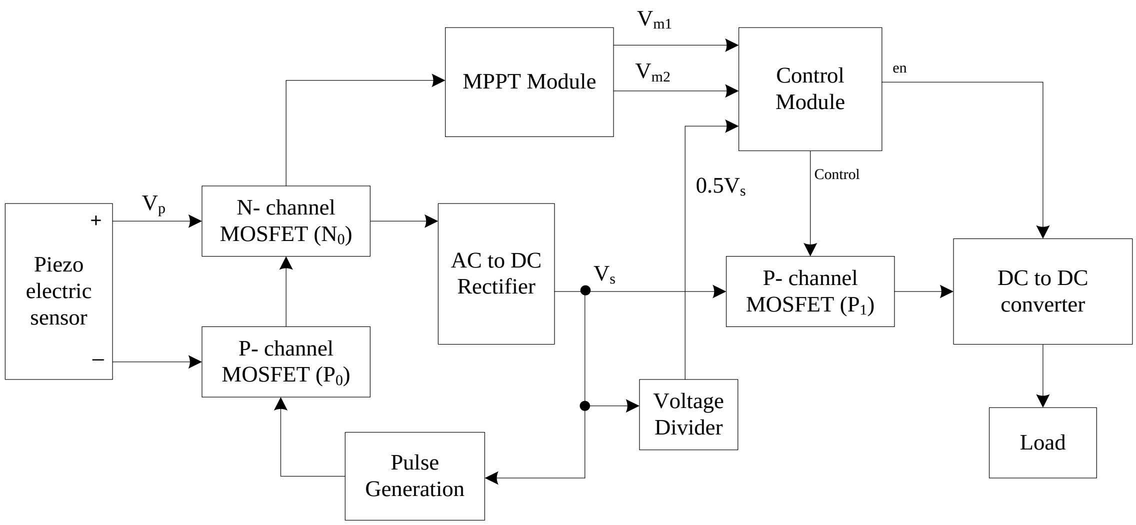



Figure 1. Overall PE-based energy harvester system using MPPT

When the enable (en) signal is low and the load application moves into the idle mode, at the same time, it will store the status of the load. The DC-to-DC converter provides a small power supply to run the load application continuously. The optimal voltage is less than 2 $V_{m2}$, and at the same time control signal becomes high and puts MOSFET $P_1$ to turn off to complete the first cycle of operation. So, the capacitor $C_s$ charges the harvested power, and then its optimal voltage reaches greater than $2V_{m1}$, and the same process repeats continuously. The PE sensor, energy harvester, and MPPT are explained in the following sub-sections.

### 2.2. Piezoelectric model

The main component of the energy harvesting system is a piezoelectric sensor, which uses ambient vibrations to generate an electric voltage. The application relies on a PE sensor that measures pressure, temperature, force, strain, and other physical variables. PE provides more excellent durability, strength, lightness, and flexibility. The PE sensor uses the direct piezoelectric effect. The PE sensor is effective in most low-power applications because it has a superior signal-to-noise ratio cancellation and noise rejection capability. The PE sensor mainly contains input AC source in parallel with capacitance '$C_p$' and resistor '$R_p$'. The PE sensor circuit is added with interface circuit, to alter the sensor's higher impedance output to a small one also amplifies the sensing signals by removing the unwanted signals. Compared with data acquisition system operating frequencies, the capacitor provides very high impendence at sensor output. The PE sensor electrical model is represented in Figure 2.

The input AC is defined using vibration magnitude ($I_p$) and input frequency (f). So, AC source is $I_{ac} = I_p \sin(2\pi ft)$. The AC signal is generated at the end of the PE sensor output voltage because of the input AC source and variations in the magnitude of the vibration. The PE sensor output ($V_p$) is proportional to the vibration magnitude '$I_p$' and inversely proportional to PE capacitance and input frequency. The PE output voltage is obtained using (1) as [10]:

$$V_p = \frac{Q}{C_p} \approx \frac{I_p}{2\pi f C_p} \tag{1}$$

The 'Q' charge is applied to the PE sensor Q = (Ip/2πf), the PE capacitance and load resistor values like 30 nF and 100 kΩ, respectively, are considered for modeling the PE sensor circuit.

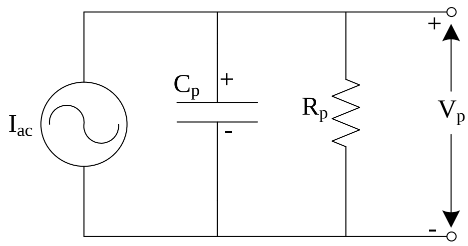



Figure 2. The electrical model of the PE sensor

### 2.3. Piezoelectric energy harvester model

The PE sensor circuit generates the AC voltage, but the energy capacitor stores only DC voltage. So, the AC to DC rectifier is introduced to convert the AC to DC voltage. The PE sensor generates a lower voltage for the given time to operate the applications. So, there is a need for capacitor Cs, which are added in parallel with the rectifier circuit. The capacitor (Cs) accumulates the collected power in the EH system. The piezoelectric energy harvester (PE-EH) model is represented in Figure 3. The harvested power across the capacitor is represented by (2) [10]:

$$P = \frac{2I_pV_s}{\pi} - 4V_s^2 f C_p - 8V_s D_v f C_p \tag{2}$$

where $I_p$ is the vibration magnitude of the PE sensor, $D_v$ is the voltage drop across the diode (forward), $f$ is input frequency, $C_p$ is PE capacitance, and $V_{s.}$ is the optimal voltage of the PE-EH output. The optimal peak voltage is represented in (3) to collect the maximum harvested power. The maximum harvested power is directly proportional to the vibration magnitude ($I_p$) and inversely proportional to the frequency. The '$I_p$' and '$f$' values are not constant and continuously varied based on the time and ambient vibrations.

$$V_{s,peak} = \frac{I_p}{4\pi f R C_p} - D_v \quad (3)$$

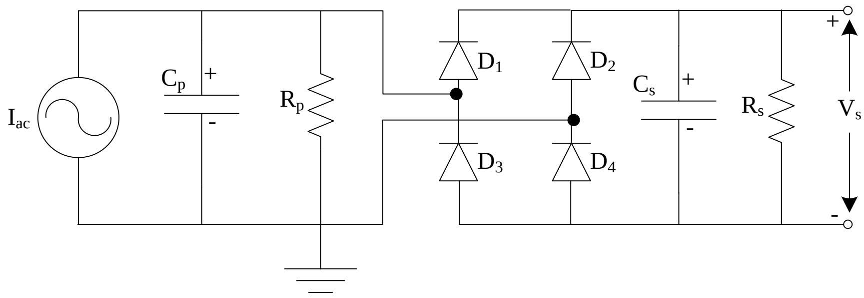



Figure 3. Piezoelectric energy harvester (PE-EH) model

## 2.4. MPPT model

The MPPT generates the required power by absorbing environmental vibrations. The MPPT does not require a battery and automatically supplies the necessary power to the system's activities. The MPPT is used to keep track of the PE-maximum EH's power (optimal voltage). To track the ideal voltage, a time multiplexing method is used. The PE sensor output ($V_P$) is disconnected occasionally from the application, and it is not easy to track the optimal voltage in the EH system. So MPPT is used to periodically connect the PE sensor circuit to follow the optimal voltage ($V_s$). The MPPT electrical model is represented in Figure 4. The capacitor and resistors are connected parallel to the PE sensor output to generate the MPPT output ($V_m$).

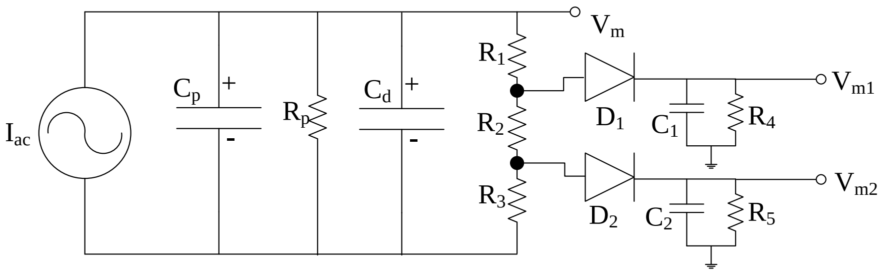



Figure 4. MPPT electrical model

The MPPT output voltage $V_m$ and its maximum peak voltage $V_{m,\text{ the peak}}$ is represented in (4) and (5) respectively as [10]:

$$V_m = Ip \frac{R}{\sqrt{1+(2\pi f R C_p)^2}} sin(2\pi f t + \theta) \quad (4)$$

$$V_{s,peak} = \frac{I_p}{2\pi f R C_p}; if\left(2\pi f R C_p \gg 1\right) \quad (5)$$

The optimal voltage $V_s$ obtained from (5) and represented in (6) as:

$$V_s = \frac{V_{m,peak}}{(2-D_v)} \quad (6)$$

The optimal voltage $V_{s.}$ can be obtained using the maximum peak voltage of MPPT, which is used to track the vibrations. The $V_{s.}$ is acting as source voltage to the control module. The control module receives two reference voltages ($V_{m1}$ and $V_{m2}$), and these values should be lesser than the optimal voltage ($V_s$) to perform the correct operations. The parallel connection of capacitor $C_d$ and resistors ($R_1$, $R_2$, and $R_3$) are included in PE sensor output to reduce the two reference voltage values. The MPPT output voltage is represented in (7) as [10]:

$$V = \frac{I_p}{4\pi f R C_p} \tag{7}$$

The equation (7) is obtained by satisfying the condition (*2πfR* ($C_p$ + $C_d$) *>>1*). Where equivalent resistance (R = $R_1 + R_2 + R_3$). The reference voltages are obtained by placing the low pass filter and voltage divider and are represented in (8) [10]:

$$V_{m1} = \frac{I_p}{8\pi f R C_p} - D_v + \sigma \text{ and } V_{m2} = \frac{I_p}{8\pi f R C_p} - D_v - \sigma \tag{8}$$

A small voltage σ=$R_2/R_1+R_2+R_3$ and $D_v$ is the diode's voltage drop (forward). These reference voltages $V_{m1}$ and $V_{m2}$ are used to track the maximum point in control module.

## 3. RESULTS AND DISCUSSION

The overall PE-based EH system using Simulink is represented in Figure 5. The optimal voltage stored across capacitor $C_s$ is initially zero, even with the ambient vibrations. So, the pulses generator will not be activated using $V_s$, leading to MOSFETs $P_0$ and $N_0$ will be on and off-state, respectively. Simultaneously, the PE sensor provides the sensor voltages to the harvester system to run the operations. The PE sensor current reaches the capacitor $C_s$, and it gets charged. When $V_s$ value is increasing, and at some point, it provides optimal voltage to the pulse generator. The overall PE-based energy harvester and its submodules are verified in each stage to analyze the simulation results and are discussed in graphical representations.

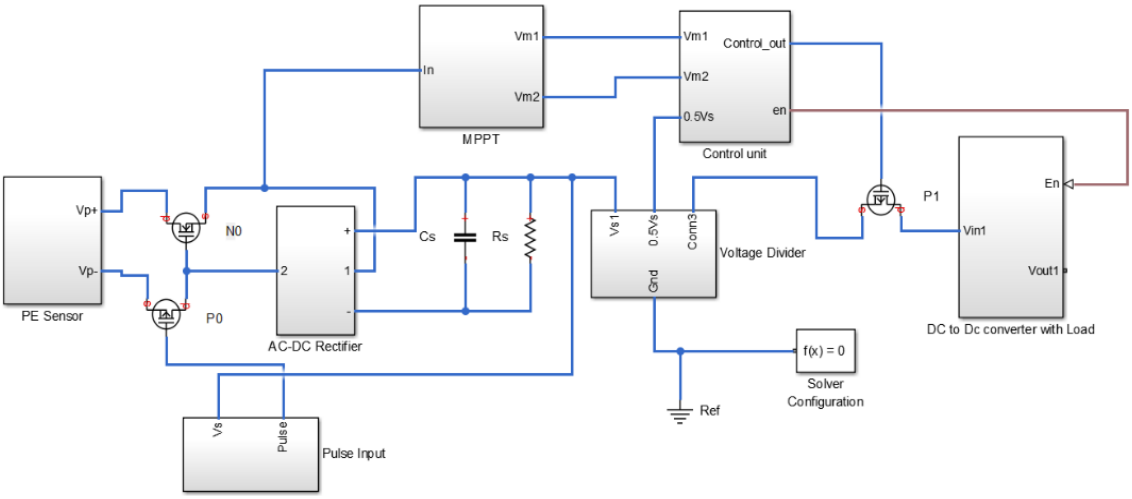
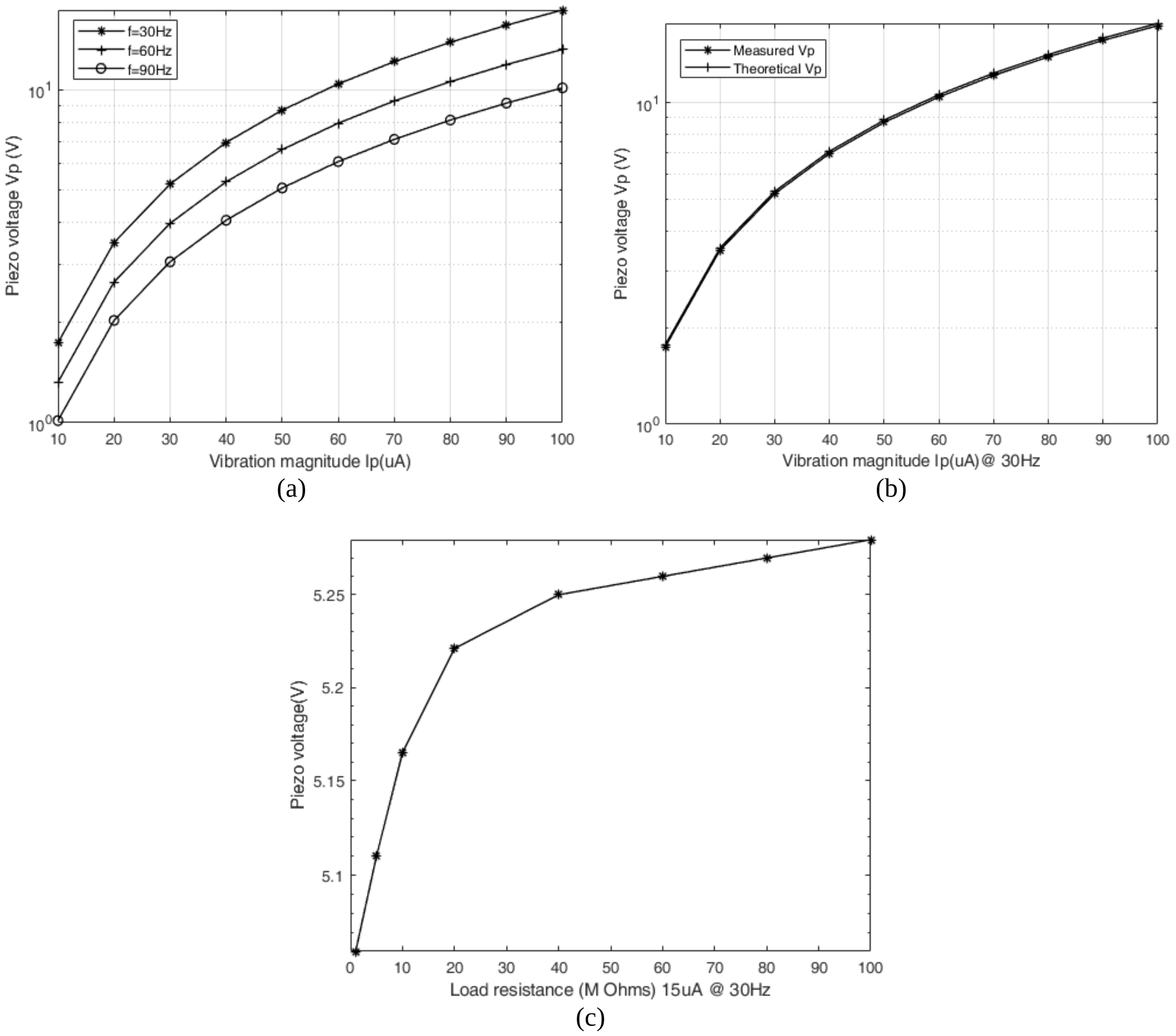



Figure 5. PE-based energy harvester model using Simulink

The $V_p$ v/s $I_p$ plot for different frequencies (30, 60, and 90 Hz) is represented in Figure 6(a). The PE sensor voltage ($V_p$) increases linearly with the input current source, and it is inversely proportional to the frequency of the source vibration magnitude $I_p$. A decrease in the frequency of vibration magnitude raises the PE sensor voltage. For varied vibration magnitudes and frequencies, the PE sensor voltage ranges from 1.015 to 17.39 V. There are minimal differences in theoretical and observed PE sensor voltage at different frequencies, as shown in Figure 6(b). The PE output voltage ($V_p$) is varied, and the resistive load variation influences it. The PE sensor voltage varied from 5.06 to 5.27 V for load resistance of 1 to 100 MΩ with 15 µA at 30 Hz, represented in Figure 6(c).

The PE-energy harvester module collects the optimal voltage ($V_s$) across the capacitor $C_s$. The voltage $V_P$ is inversely proportional to the constant PE capacitance frequency and directly proportional to the vibration magnitude. So, the optimal voltage linearly by concerning the $I_p$. The optimal voltage $V_p$ obtained from 0 to 0.9 V for the $I_p$ ranges from 10 to 100 µA, stored across the $C_s$, and is represented in Figure 7(a). The power obtained for the PE-based EH module is directly influenced by vibration magnitude, optimal voltage, and PE capacitance parameters. As the input vibration magnitude increases, the amount of harvested power also increases. The instantaneous harvested power is obtained from the range 0 to 51 µW for the vibration magnitude ranges from 10 to 100 µA, and it is represented in Figure 7(b). The amount of harvested power is decreased by increasing the frequency of the vibrations. The PE-based EH module's simulation results are carried out for different magnitude frequencies to obtain the optimal voltage and power.

The instantaneous output voltage $V_m$ provides the output voltage stored in MPPT. The output voltage $V_m$ is directly proportional to the vibration magnitude. As the vibration magnitude increases, the MPPT voltage $V_m$ value increases linearly, plotted in Figure 8(a). The MPPT voltage $V_m$ obtained the ranges from 0.76 to 9.62 V for the $I_p$ ranges from 10 to 100 µA. The MPPT voltage $V_m$ is inversely properly to the frequency and varies directly with PE resistance, so the MPPT voltage decreases as frequency increases. The MPPT module's power consumption is determined by the instantaneous output voltage $V_m$. The $V_m$ and $I_p$ have a direct connection, which is used to determine power. Because the MPPT voltage is inversely proportional to the frequency, the power produced decreases as the frequency rises. The instantaneous power is obtained for MPPT from the range 0 to 54 µW for the vibration magnitude ranges from 10 to 100 µA, and it is represented in Figure 8(b).




(a) (b) (c)

Figure 6. PE simulation results (a) $V_p$ v/s $I_p$ plot (b) theoretical and measured $V_P$ v/s $I_p$ plot, and (c) $V_P$ v/s load resistances plot

The simulation results in the overall PE-based EH system is represented in Figure 9. The voltage across the PE sensor and storing capacitor $C_s$ is achieved with the MPPT unit and N-MOSFET. The PE sensor voltage ($V_p$) varies from 1.02 to 12.9 V, and it is inversely proportional to frequency and directly proportional to the $I_p$ values. The $V_p$ v/s $I_p$ plot for the overall PE-based EH system is represented in Figure 9(a). The $V_p$ voltage value must be positive range to operate the comprehensive system. The optimal voltage ($V_s$) across storing capacitor is calculated with $I_p$, frequency, and $C_p$. The optimal voltage ($V_s$) stored in capacitor $C_s$ varies from 0.12 to 1.6 V and is represented in Figure 9(b). The overall harvested power obtained for the complete EH system is up to 86 µW for the vibration magnitude ranges from 10 to 100 µA, represented in Figure 9(c).

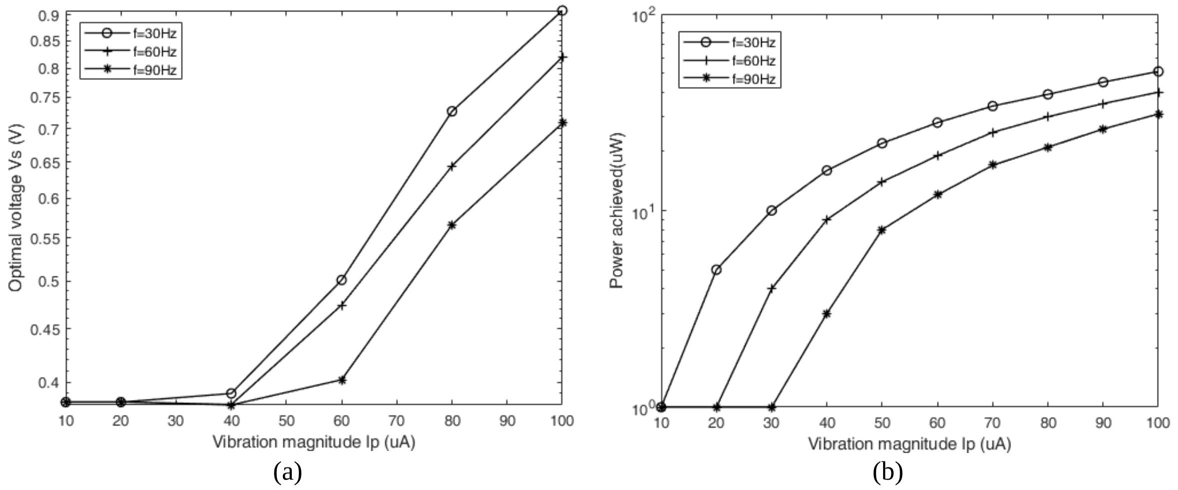



Figure 7. PE-energy harvester simulation results: (a) $V_s$ v/s $I_p$ plot and (b) power achieved v/s $I_p$ plot for different input frequencies

The summary of the PE-based EH module and overall self-powered EH system is tabulated in Table 1. The comprehensive EH system can harvest up to 43 to 86 µW power and store up to 1.6 V optimal voltage across the storage capacitor. The performance comparison of the proposed EH with existing EHs is tabulated in Table 2. The harvester type, self-power feature, obtained optimal voltage, and harvested power is used for performance comparison.

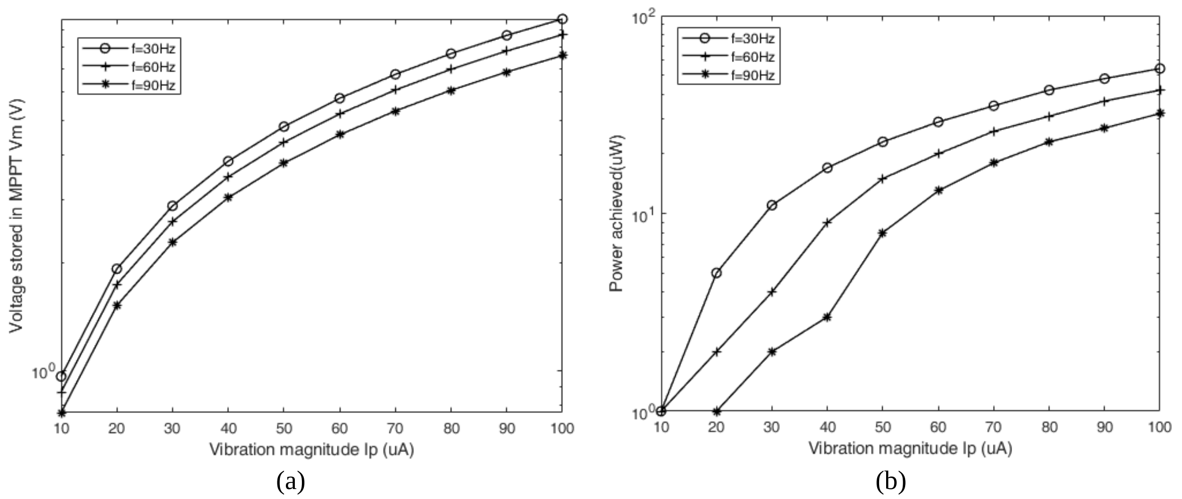



Figure 8. MPPT Simulation results: (a) $V_m$ v/s $I_p$ plot and (b) power obtained v/s $I_p$ plot for different input frequencies

The PE-EH system [17] is designed with a full-bride rectifier with the control circuit. The system obtains the optimal voltage of 0.694 V with 11.1 µW power. The Bride vibrations based PE-EH system [20] brings the power of 0.2 µW with 4 V optimal voltage. The MPPT based PE-EH system [22] produces the 30.53 µW power for 1.6 V. The PE-EH with a self-powered system is designed to harvest the 36.8 µW of power for 0.7 V. The tribo-electric (TE) based EH system is designed and harvests the power of 0.2 µW for 1.45 V. The proposed PE-EH system is designed using MPPT with a self-powering feature and produces the harvested power of 86 µW for 1.6 V. The existing PE-EH system uses different vibration types at different input frequencies to achieve the optimal voltage and power. The proposed design reaches better voltage and power for low-power applications than the existing EH systems.

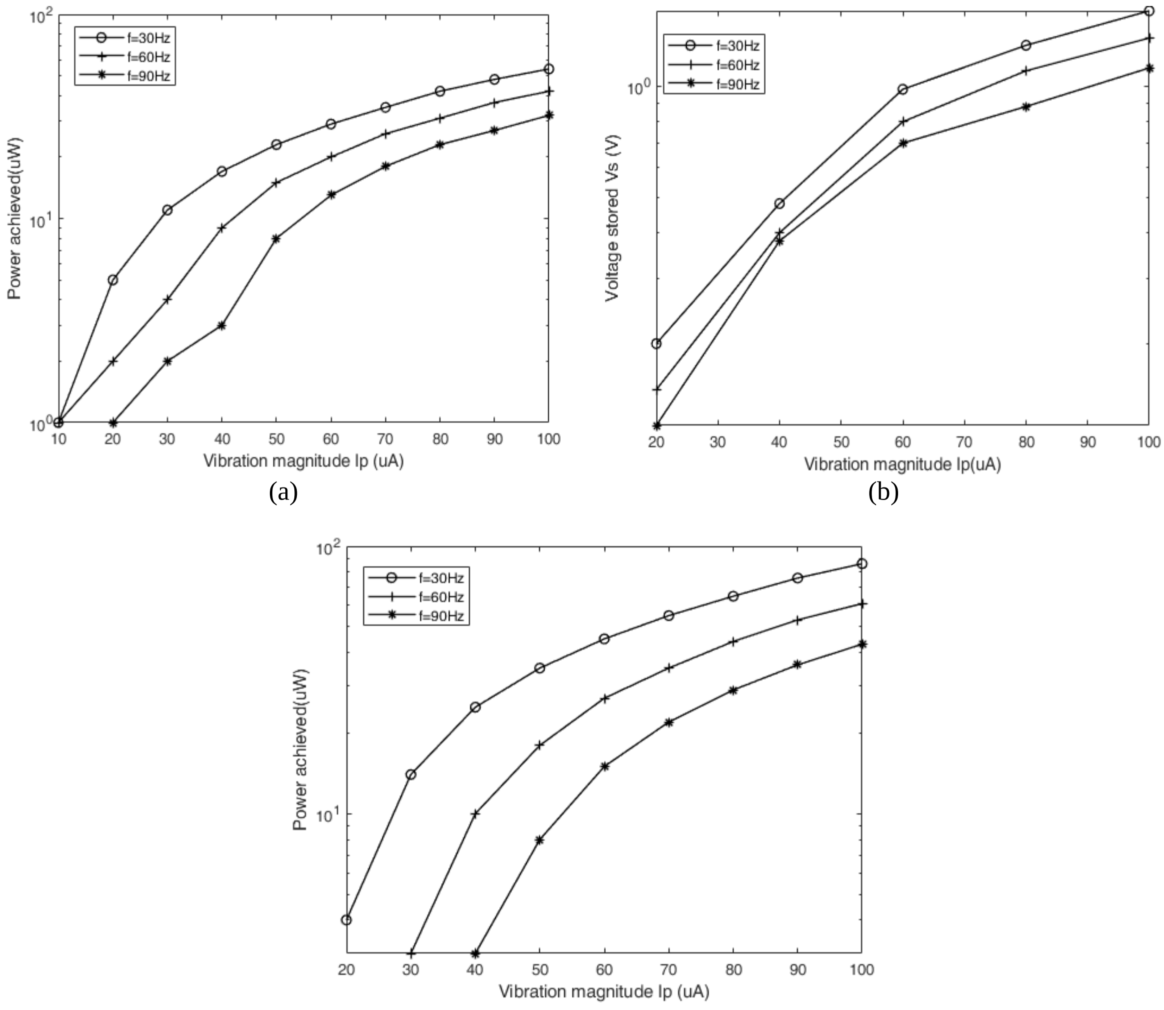



Figure 9. Overall simulation results: (a) $V_p$ v/s $I_p$ Plot, (b) $V_s$ v/s $I_p$ plot and (c) power obtained v/s $I_p$ plot

Table 1. Summary of PE-based EH module and overall EH system

| Modules | PE sensor voltage (V) | Optimal voltage (V) | Harvested power (µW) |
|---|---|---|---|
| PE-based EH module | 17.39 | 0.9 | 51 |
| Overall PE-based EH system | 12.9 | 1.6 | 86 |

Table 2. Performance comparison of the proposed EH with existing EHs

| Designs | Harvester type | Self -powered | Optimal voltage (V) | Harvested power (µW) |
|---|---|---|---|---|
| [17] | PE | No | 0.694 | 11.1 |
| [20] | PE | No | 4 | 0.2 |
| [22] | PE | Yes | 1.6 | 30.53 |
| [27] | PE | Yes | 0.7 | 36.8 |
| [28] | TE | No | 1.45 | 0.2 |
| This work | PE | Yes | 1.6 | 86 |

## 4. CONCLUSION AND FUTURE WORK

In this manuscript, an efficient Piezoelectric-based energy harvester system is designed using the MPPT approach. The overall system mainly includes PE sensor circuit, AC to DC rectifier, MPPT module, control module, DC to DC converter, and load applications. The N-channel and P-channel MOSFETs are used in the MPPT module to track the optima voltage points. The experimental simulation results are carried out individually for the PE sensor circuit, PE-EH module, and overall PE-EH system for the range of 30 to 90 Hz with a vibration magnitude range from 10 to 100 µA. The voltage storage across the capacitor and power harvested from ambient vibrations are analyzed in detail. The PE voltage was obtained in the range of 1.015 to 17.39 V using a PE sensor. The PE-EH module receives the optimal voltage of 0.9 V and harvests the power up to 51 µW. The MPPT obtains the output voltage up to 9.62 V and power of 54 µW. The overall PE-based EH system stores the voltage of 1.6 V and gets the harvested power of 86 µW. In the future, more voltage storage across the capacitor and better-harvested power can be achieved using different ambient vibrations. The bio-mechanical vibrations are included in the proposed energy harvesting system to run low-power applications.

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