LOW POWER ENERGY HARVESTING USING PIEZOELECTRIC SENSORS FOR MEDICAL IMPLANTS

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Abstract**—— *Low Power Energy Harvesting Using Piezoelectric Sensors for Medical Implants to convert ambient mechanical vibrations into usable electrical energy. The system consists of a sequence of components designed to efficiently process and utilize the harvested energy. Initially, the piezoelectric sensor captures mechanical vibrations and generates an alternating current (AC) signal. This signal is then rectified to direct current (DC) using a full-wave diode bridge rectifier. The rectified output is filtered through a capacitive filter to smooth the voltage, which is subsequently regulated by a buck-boost converter to stabilize and adjust the voltage level. The stabilized 5V output from the buck-boost converter powers an Arduino Uno microcontroller, which is used to control and monitor the system. The Arduino Uno interfaces with a driver circuit, which in turn drives a 5V power supply connected to a separate driven circuit. This driven circuit is also linked to another buck-boost converter to further condition the voltage for optimal performance. A capacitor bank is employed to store the regulated energy, which is then supplied to the load. The system incorporates a voltage sensor connected to the Arduino Uno to continuously monitor the voltage levels. The Arduino Uno processes this data and displays real-time voltage readings on an LCD display, providing an intuitive interface for monitoring the energy harvesting system's performance. The input frequency measured from the energy scavenging system is 2Hz-20Khz and output voltage is 3 to 5 volts. This energy is given to the medical implant. The harvested and stored energy is utilized to power low-power implantable medical devices, such as pacemakers or biosensors. For instance, a piezoelectric energy harvester can convert the mechanical energy from heartbeats into electrical energy to power a pacemaker, potentially eliminating the need for battery replacement surgeries.***

Keywords—Energy scavenging, Piezoelectric sensor, Bridge rectifier, Buck- boost converter, Arduino uno, LCD.

I. INTRODUCTION

All of these technology advancements in medical fields have consequentially lead to the need of dependable and sustainable power sources for implantable medical tools. Conventional implants powered by batteries are constrained by short lifetimes, repeat replacements, and the related surgical risks.

Deploying piezoelectric sensors for low-power energy harvesting is a potential solution that exploits the body's natural mechanical movements, including heartbeats, muscle contractions, and respiratory motions, to produce electrical energy. Body Piezoelectric nanomaterials can convert mechanical stress to electrical voltage so they can be used in self-sustained biomedical applications. Thus, this technology overcomes the limitations of conventional batteries by harvesting energy from physiological activities, which leads to lower maintenance costs, reduced electronic waste, and fewer surgical interventions for battery replacement. Also, combining piezoelectric energy harvesting with real-time monitoring systems allows for ongoing tracking of important health metrics, which boosts patient safety and improves medical efficiency. As healthcare moves towards smarter, more independent, and eco-friendly solutions, piezoelectric energy harvesting stands out as a key innovation for the future of implantable medical devices.[1][4][20][23]

II. LITERATURE SURVEY

The objective of this paper is to investigate the feasibility of using vibrations as sources of energy for the deployment of energy self-sufficient wireless sensing platforms in the context of the Industrial Internet of Things. In this context, this paper suggests the deployment of piezoelectric sensors on vibrating assets, such as machinery, to create energy self-sufficient sensing platforms in hard-to-reach locations. Preliminary measurements and further laboratory tests are proposed for understanding the behaviour of commercial piezoelectric sensors as energy harvesters. A general architecture for vibration-powered LoRa WAN-based sensor nodes is discussed first. Final tests to achieve an optimal trade-off between sensor sampling rates and energy availability are conducted later. The objective is to operate the device continuously and at the same time to maintain a charging trend of the storage component that is connected to the system. In this context, an Ultra-Low-Power Energy-Harvesting Integrated Circuit assumes a crucial role in ensuring the proper regulation of the output with a very high level of efficiency.

This paper discusses a high-performing piezo- and pyroelectric nanogenerator (PPNG) comprised of electrospun PVDF nanofibers integrated with interlocked micro-electrodes and doped with multi-wall carbon nanotubes (MWCNT). The device exhibits an output voltage of over 35 V, a power density of around 34 µW cm^{-2}, a piezoelectric conversion efficiency of approximately 19.3%, and a response time of around 10 ms, thus outperforming neat PVDF nanofibers in piezoelectric charge coefficient. It can power electronic devices such as capacitors and LEDs, and is embedded in an IoT-based biomedical system for real-time monitoring of vitals (such as pulse, temperature) and reactions (such as coughing, laughing) wirelessly via mobile. Applications can be as critical as those in the intensive care management plan for pneumonia specifically under the conditions that can arise during COVID-19 through wearable health monitoring solutions.

Modern healthcare systems are transitioning from a hospital-centric model to a more individual-focused model. The future implantable and wearable medical (IWM) devices are the major components of such types for affordable and accessible healthcare. It would help in the continuous monitoring of clinically significant physiological parameters for early disease diagnosis and preventive measures. Most of the IWM devices, however, are battery-powered; these run out and must be replaced, disrupting the normal functioning of the medical devices. Uninterrupted energy supply becomes essential for operating medical devices continuously for a Longing period. Performing high-level real-time activity of IWM devices and extending the lifetime would be dependent on a sustainable, health-compatible energy supply. Thus, harvesting energy from the human body and the ambient environment is the need for long-lasting precision healthcare while maximizing user comfort. That converts various sources' energies to their corresponding electrical form. This paper reports a state-of-art comprehensive review of energy harvesting techniques focusing on the medical applications. Several energy harvesting methods, working principles, and current states will be analyzed focusing on their advantages and limitations. In addition, current challenges and prospects for improvement are outlined. This paper will help toward an understanding of energy harvesting technologies for developing portable medical devices with high efficiency and reliability, robustness, and battery-less capability.

Energy limitations challenge advancement of wearable technologies everywhere including in smart healthcare, military, infotainment and other industries. Energy harvesting solves this challenge by converting the energy from diverse ambient sources like heat, vibration, solar, and radio waves into usable energy. Among these methods, hybrid solar (SWEH) and thermoelectric (TWEH) make up for more than 501 mW output, while piezoelectric fabrics are light and comfortable, operating at power up to 29.7 µW/cm^3. Radiofrequency harvesters still require further development for higher power outputs. Wearable energy harvesters span a few millimeters to centimeters with operating ranges of 1- 1400 Hz; hybrid systems achieve the maximum power densities due to combined solar - thermoelectric conversion.

Recent changes in technology have led to tremendous changes in society and cities. Information and communication technology (ICT) forms the hub of smart cities, facilitating secure and efficient communication enabled by both 5G and IoT networks. But how self-powered sensing devices can be kept up in state-of-the-art operation remains a riddle yet to be solved. These piezoelectric energy harvesters are soaring head-high towards their feasible merit of power, with which they can operate wireless sensor nodes and many applications like smart transport, heath care, human-machine interfaces, and security systems. They can, in most cases, provide sustainable power and can also energize intelligent and self- powered sensors for different uses. The present paper discusses piezoelectric energy harvesters in their role of powering IoT sensors and devices by focusing on these developments as they apply to smart city infrastructures and in the course of those focusing on advancing energy sustainability.

The study investigates piezoelectric materials to supplement gross energy demands, generating clean energy, and reducing global warming. Thanks to these materials, piezoelectric mechanical energy conversion allows pressure and vibration from human activity (e.g., walking or cycling) to induce electrical energy. For the purpose of the study, a stationary exercise bike using a piezoelectric generator was built for the purpose of energy transformation and storage, producing 13.6 mW for typical cycling rates or lifting 11.5 V at 1.2 mA, which could charge 3200 mAh, 5 V battery capacity and power sensors. This system transforms bicycles into smart, micro-mobility vehicles, indicating a point of action in becoming effective for renewable energy in low-cost applications and smart-city infrastructure overall.

III. PROBLEM STATEMENT

Among the promising technologies to capture ambient mechanical energy and convert it into electrical power, piezoelectric energy harvesting is one technology that has drawn much attention in recent years. Critical for powering small-scale low-power devices like wireless sensors, medical implants, and wearable devices, it's at times impractical or not available to be used through the traditional power source. Despite all the promises that this technology holds, it is still facing major challenges which prevent it from being widely accepted and applied. In most systems that work with low- frequency vibrations or irregular mechanical inputs, the efficiency of mechanical to electrical energy conversion is low. Piezoelectric device outputs are mostly unstable and intermittent, thus requiring the need for energy storage and management towards a reliable power supply. Some key problems include: energy storage devices, in the form of capacitors or batteries that are assumed to store then recover harvested energy efficiently, and more robust piezoelectric material against both operational stresses such as temperature, humidity changes, and environmental stress, that is cyclic fatigue.[14]

Another challenge in this regard is that the scalability of piezoelectric devices will be optimized mainly because the present piezoelectric systems are tagged by the constraint of limited output power and reduced efficiency in performance at larger scales of applications. Piezoelectric energy harvesting will definitely become a viable solution at the real-world application scales only when it will be adequately integrated along with the existing electronic systems as well as cost-efficient scalable designs. These are being overcome by designing more efficient materials, by optimizing energy harvesting mechanisms and creating advanced power management systems that can store and exploit the harvested energy over significant periods.[7][14]

IV. IMPLEMENTATION AND DESIGN

In developing a piezoelectric energy harvesting system, proper selection of the material, mechanical design consideration, and efficiency of electrical components are of significant importance. The most significant point in maximizing energy conversion through this source is the selection of a piezoelectric material. Piezoelectric (PZT) material allows for high energy output. PVDF is the best alternative for wearable or flexible applications. The mechanical design captures and transfers mechanical energy often through structures such as cantilever beams or mechanical amplifiers to enhance the strain in the piezoelectric material. These components must be tuned to resonate at the ambient vibration frequency for maximum energy extraction. The electrical design captures the AC produced by the piezoelectric material and converts it into direct current (DC) that can be stored or used directly. A bridge rectifier is the most widely used for this conversion, and energy storage components include capacitors, super capacitors, or rechargeable batteries that have to store the harvested energy.[3][17]

Without power management circuits, it cannot be regulated. This prevents the harvested power from being stored efficiently and used appropriately. For example, boost converters may be used to step up that low voltage produced by the piezoelectric material, say to charge battery banks or power electronic devices, etc. Energy harvesting is thus optimized if the mechanical as well as electrical components are used in a harmonious balance. The system should be tuned in such a way that the mechanical vibrations in the surrounding environment are to be matched in order to get energy harvesting as a wide range of frequency vibrations. For this purpose, wide-bandwidth piezoelectric materials may also be utilized. The whole structure needs to be packed for protection from environmental influences like moisture or high temperatures, which may degrade the piezoelectric material performance. There are practical factors such as durability, efficiency, and scalability that need to be met so that it can sustainably work with time and in different types of environments. For example, in industrial environments, the system needs to stand continuous mechanical stress while being able to continue its function of harvesting energy. Thus, these piezoelectric energy harvesting systems, with thoughtful designs and integrations, offer sustainable and reliable sources of power for a wide range of devices, from microsystems to large industrial system installations.[5][13][19]

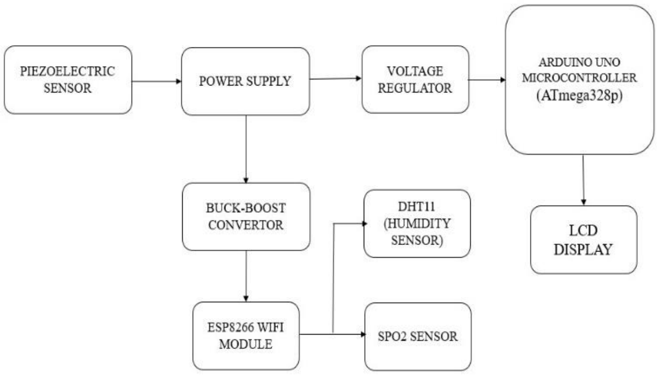


Figure. 1. Block Diagram piezoelectric energy scavenging system.

The Figure. 1. depicts the Block Diagram of the Piezoelectric Energy Scavenging System. This system contains a, transformation mechanism that transforms the input signal into an understandable output. So from the block diagram each contents function is summarized.[8]

Piezoelectric sensor is used to convert mechanical vibration into electrical energy. It is powered by the body movements or the external forces, thus producing a low-voltage output that is the sole power source for the system. The technology eliminates the use of traditional battery-powered medical devices, and the system is sustainable.[4][6][10]

The power supply module takes the electricity generated by the piezoelectric sensor and regulates its dissemination to the remainder of the apparatus. Since raw energy output by the sensor is potentially unstable, this module allows a stable provision of power for the rest of the system.

The voltage regulator regulates the unstable power from the power supply to provide the microcontroller and the sensors with a stable voltage to operate. It shields delicate electronic components from damage by not allowing overvoltage and undervoltage state.

The processing unit of the system is the Arduino Uno (ATmega328p). It gets input signals from the SpO2 sensor and the DHT11 humidity sensor, processes them, and gives the required information to the LCD display and the IoT platform. It also controls data exchange between different components for smooth operation.

The buck-boost converter operates to control voltage levels, boosting or bucking the input voltage supplied to ensure constant power supply. Since the energy harvested by the piezoelectric sensor can be in a form that is not always compatible with the voltage required, this device provides compatibility with other devices in the circuit.

The ESP8266 WiFi module provides wireless connectivity, so the system is able to send real-time data to the Blynk IoT platform. This capability allows remote monitoring of health parameters such as temperature, humidity, heart rate, and SpO2 levels, thus making it an efficient feature in telemedicine and remote patient monitoring.

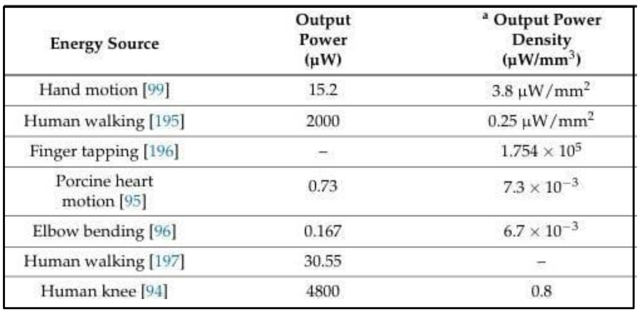
DHT11 sensor is employed to measure humidity and temperature in the ambient air. It is employed to monitor conditions that may impact a patient's health, especially in medical applications where environmental conditions matter the most. The data that is collected is processed by the microcontroller and then displayed on the LCD display or transmitted to the IoT platform.

The SpO2 sensor detects blood oxygen saturation and heart rate (BPM), offering vital health information. It is of great importance in the patient monitoring of respiratory or cardiovascular disease, where it helps in identifying oxygen saturation and pulse rate abnormalities.

The LCD screen is used to show real-time readings of the sensors, such as temperature, humidity, BPM, and SpO2 levels. Besides that, it also has a local monitoring function that enables users to view health indicators in real-time without internet access. This module - based design allows effective energy harvesting, real-time health monitoring, and wireless IoT connectivity, and the system is an independent, wireless medical monitoring system.[2][9][12]

From the data gathered, Arduino has illuminated an LED as displayed in Figure 1, to indicate immediately if there is a presence or presence of stress. Moreover, the processed information is relayed to an LCD, which could be configured to display the type of force being exerted in real time. This configuration is suitable for applications in structural health monitoring, material testing, and many other branches of engineering where monitoring of notable force levels is pertinent either to safety or performance.

Table. 1. Tabulation of power obtained by various piezoelectric sensor



Energy Source	Output Power (μW)	ᵃ Output Power Density (μW/mm³)
Hand motion [99]	15.2	$3.8\ \mu W/mm^2$
Human walking [195]	2000	$0.25\ \mu W/mm^2$
Finger tapping [196]	–	1.754×10^5
Porcine heart motion [95]	0.73	7.3×10^{-3}
Elbow bending [96]	0.167	6.7×10^{-3}
Human walking [197]	30.55	–
Human knee [94]	4800	0.8

The piezoelectric energy scavenging system for medical IoT adopts the mechanical energy from the patient's motion or vibrations, refer Table. 1. Tabulation of power obtained by various piezoelectric sensor and then converts it into electrical energy for the IoT device to operate with no external power supply.

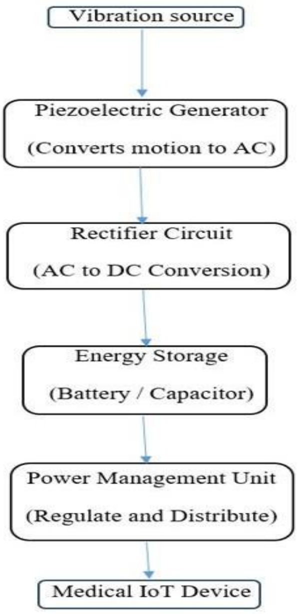


Figure. 2. Flowchart of piezoelectric energy scavenging system.

The figure. 2. depicts the flowchart of piezoelectric energy scavenging system, at first, starts with the basic mechanical energy obtaining through movement, (for example, walking and body vibrations) by piezoelectric generators. These generators are the ones to convert the mechanical energy to AC. The DC power is then stored in the energy storage unit such as a battery or supercapacitor for use in later times. The PMU plays the role of efficient energy distribution, supplying a steady level of power to the medical IoT devices, and regulating the voltage. This may consist of sensors or health monitor worn on the body that are able to extract significant health data such as heart rate, temperature, and fatigue. The processed data offers healthcare providers real-time health insights, alerts, and feedback. The system enhances the flows of patients that are monitored without the imposition of periodical charging and aids in the establishment of self- sustaining medical IoT devices.[15][18][22]

V. RESULTS AND OUTPUT

The systems mechanical vibration is converted to usable electrical energy through the use of a piezoelectric sensor, which captures these vibrations and converts them into an alternating current signal. This AC signal is rectified to DC. The waveform is sinusoidal, oscillating from positive to negative voltages.

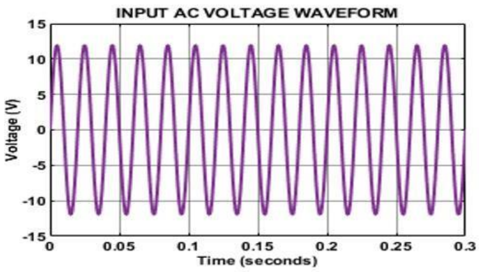


Figure. 3. Input AC voltage waveform over time

The voltage values range from around -12V to +12V, and repeats the waveform at regular time intervals. The Figure. 3. Input AC voltage waveform over time is given above, this type of waveform is commonly used in an AC power system where the voltage switches direction at a set frequency to provide electrical power. On the horizontal axis is seconds for time, and on the vertical axis is the magnitude of voltage.

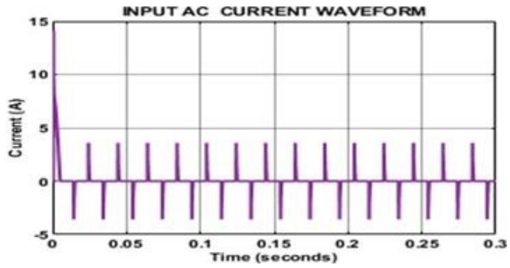


Figure. 4. The AC current input waveform versus time.

The waveform seems to be a set of rectangular pulses, refer Figure. 4. The AC current input waveform versus time, where the current is alternating between positive and negative values. The pulse width and amplitude seem constant throughout the time interval considered. This type of waveform is characteristic of AC current, where the direction of the flow periodically reverses. The horizontal axis represents time in seconds, and the vertical axis shows the current magnitude in Amperes.

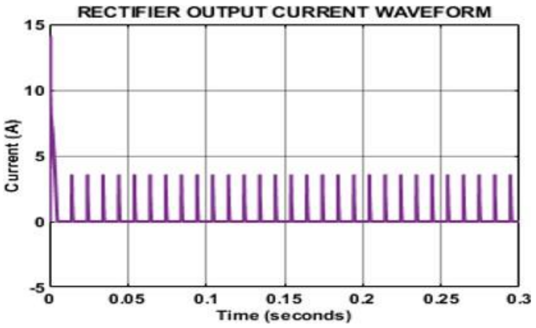


Figure. 5. Rectifier Circuit Output Current Waveform

The waveform is made up of a series of positive pulses. The current alternates between about -10A and +10A at regular intervals it is given in the Figure. 5. Rectifier Circuit Output Current Waveform.

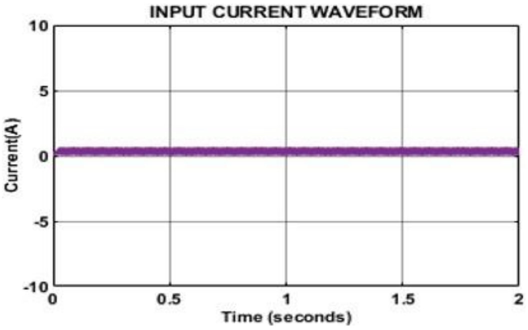


Figure. 6. Input current waveform of an electrical system

The waveform is a square wave, oscillating between positive and negative current values of approximately ±8A. This waveform often occurs in an AC circuit refer Figure. 6. Input current waveform of an electrical system, when the current's direction continuously alternates in direction. Time is indicated on the horizontal axis while the amplitude of the current is depicted along the vertical axis in terms of Amperes.

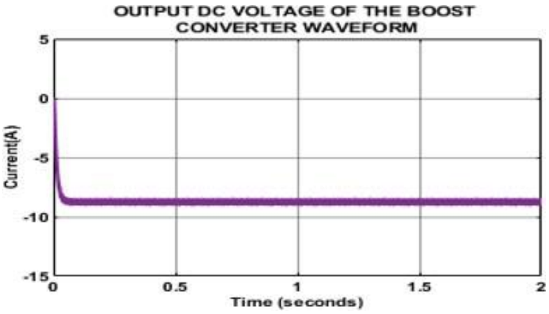


Figure. 7. Boost converter DC voltage output waveform

The above Figure. 7. Boost converter DC voltage output waveform, where the voltage goes from approximately -12V to +12V and vice versa. In boost converter, a particular type of pulsed wave is very common in its output. It steps up an input DC voltage from lesser to higher. Here again, the horizontal axis signifies time in seconds, and the vertical axis represents the magnitude of voltages in Volts. The waveform comprises a series of pulses. The current alternates from about -1.5A to +1.5A over time.[17][20][23]

The project successfully illustrates the idea of piezoelectric energy harvesting for powering medical implants, along with real-time monitoring using the Blynk IoT app as shown in the Figure. 8. The Output values obtained by Blynk IoT application.[21]

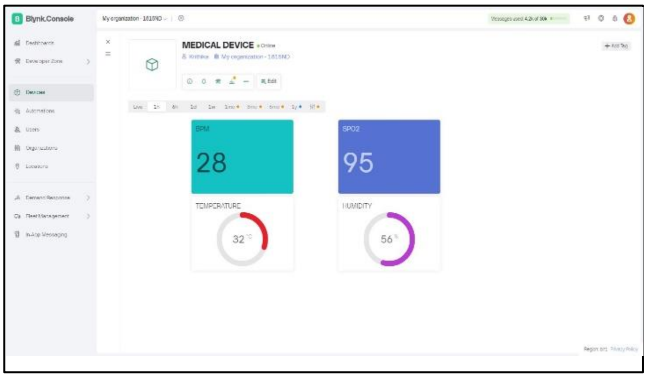


Figure. 8. The Output values obtained by Blynk IoT application

The system successfully translates mechanical vibrations caused by physiological functions into electrical energy, which is used to power sensors for temperature, humidity, heart rate (BPM), and SpO2. The values are displayed on the Blynk app, thus allowing constant monitoring of health. The constructed power harvesting circuit optimizes power extraction as well as offers a reliable power supply. Experimental results validate that the energy harvested can support sensor operation under various conditions. The incorporation of supercapacitors and thin-film batteries further enhances energy storage and hence supports continuous device operation even in the case of limited mechanical movement.[5]

The device is seamlessly compatible with medical implants and meets biocompatibility and safety requirements. Blynk IoT platform also increases user-friendliness by offering real-time remote monitoring of health data, enhancing patient care. The research confirms the viability of self-powered medical devices with IoT-based monitoring. The research opens the door to future miniaturization, energy efficiency, and clinical applications and next-generation implantable healthcare technology.[6][11][16]

VI. FUTURE SCOPE

The future scope of this project is broad, covering a series of breakthroughs that can make piezoelectric energy harvesting more efficient, beneficial, and sustainable for medical implants. The initial focus will be on increasing the efficiency of piezoelectric sensors and energy conversion circuits to tap more power output from low-intensity mechanical vibrations. In addition, miniaturization and biocompatibility research will make it possible to develop more compact, flexible, and body-compatible piezoelectric materials, thus making the technology beneficial for more implantable medical devices.[5][14][21]

Artificial intelligence (AI) and Internet of Things (IoT) integration will further enhance real-time monitoring and predictive maintenance, thus ensuring peak performance and early indication of likely problems. Another promising area is wireless power transfer, where hybrid power solutions can augment piezoelectric harvesting to provide a constant power supply without frequent battery replacement. The application scope of this technology can also be extended from pacemakers and biosensors to neurostimulators, cochlear implants, and insulin pumps, thus further increasing its application in the medical sector. In addition, improvement in energy storage, including supercapacitors and biocompatible thin-film batteries, will improve the reliability of stored energy, thus making it more suitable for long-term medical application. In the long run, regulatory approvals, clinical trials, and commercialization activities will be the catalyst in making this technology mainstream in healthcare. Finally, the research on multi-source energy harvesting, which integrates piezoelectric, thermal, and kinetic energy sources, will enhance the robustness and reliability of self-powered medical devices. Overall, these breakthroughs have the potential to transform the healthcare sector by making implantable medical technologies more sustainable, efficient, and patient-centric.[20][22]

VII. CONCLUSION

The project successfully demonstrates the feasibility of piezoelectric energy harvesting as a renewable power source for medical implants. With experimental verification, it is established that mechanical vibrations generated due to physiological functions can provide sufficient electrical power to power low-power medical devices such as pacemakers, biosensors, and health monitoring devices. The addition of the Blynk IoT app further enhances the usability of the system by providing real-time monitoring of critical parameters such as temperature, humidity, heart rate (BPM), and SpO2 levels. The input frequency is 2Hz-20Khz and the output voltage is 3 to 5 volts respectively. Energy harvesting circuit developed ensures effective power extraction and storage because the utilization of supercapacitors and thin-film batteries provides a reliable source of power even in low movement levels. Multi-source energy harvesting is also addressed in the project and it is evidenced that piezoelectric, thermal, and electromagnetic energy combined can provide greater efficiency and reliability.

In brief, the findings emphasize the promise of autonomous medical implants, obviating the necessity of frequent battery replacement and improving patient safety. Integration with Internet of Things (IoT)-based monitoring platforms, such as Blynk, further enhances usability, and the technology is thus a strong contender for next-generation healthcare applications. Miniaturization, material design, and clinical verification are fronts where future progress will serve to further refine the technology for pan-industry use in the medical field. This project, extraneously, not only provides a solution to the problems of piezoelectric energy harvesting but, also, acts as a driving force for the introduction of a better design for the use of harvested energy in biomedical applications, thus a territory for the development of advanced energy technologies.

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