

# Innovative Anemokitetics Based Free Energy System from Tree Branches Using IoT

G.Suresh 

Assistant Professor, Department of Electronics and Communication Engineering,  
Sengunthar Engineering College (Autonomous), Tiruchengode, India

[sureshg.ece@scteng.co.in](mailto:sureshg.ece@scteng.co.in)

<https://orcid.org/0009-0006-7821-2515>

M.Deepika,A.Ishwarya,S.Sasipriya

UG Scholar, Department of Electronics and Communication Engineering,  
Sengunthar Engineering College (Autonomous), Tiruchengode, India



## Publication History

Manuscript Reference No: IJIRAE/RS/Vol.13/Issue03/AEMR26.MRAE10134

Research Article | Open Access | Double-Blind Peer-Reviewed | Article ID:IJIRAE/RS/Vol.13/Issue03/AEMR26.MRAE10134

Received:22,February 2026, Revised: 01, March 2026, Accepted: 16,March 2026,Published Online: 25, March 2026.

<https://www.ijirae.com/volumes/Vol13/iss-03/55.AEMR26.MRAE10134.pdf>

**Article Citation:**Suresh,Deepika,Ishwarya,Sasipriya(2026),Innovative Anemokitetics Based Free Energy System from Tree Branches Using IoT,IJIRAE: International Journal of Innovative Research in Advanced Engineering, Volume 13, Issue 03 of 2026 pages 449-464 **Doi:->** <https://doi.org/10.26562/ijirae.2026.v1303.55>

**BibTeX Key:** Suresh@2026Innovative

IJIRAE papers should be cited as IJIRAE (International Journal of Innovative Research in Advanced Engineering, AM Publications, India 2025, ISSN 2349-2163, <https://doi.org/10.26562/ijirae.2026.v1303.55> The journal's official abbreviation is IJIRAE. **Orcid:** <https://orcid.org/0009-0004-9398-7488>

About the License: Copyright©2026 copyright by the authors. This article is an open access and license under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

**Abstract:** This project Innovative Anemokinetics based free energy system from tree branches using IoT presents an energy harvesting approach that converts wind-induced swaying of tree branches into electrical energy using piezoelectric transducers. Unlike conventional renewable systems, this method enables micro-power generation without large infrastructure, making it suitable for natural and remote environments. The feasibility of the system was validated through software-based implementation, focusing on data acquisition, monitoring, and control using an ESP8266 microcontroller. Then extends hardware realization, where piezoelectric sensors generate AC voltage that is conditioned using rectifier and voltage regulation circuits and stored in a rechargeable battery or super capacitor. IoT integration is achieved using sensors such as an anemometer, voltage sensor, and current sensor, enabling real-time monitoring and cloud-based data visualization.The result shows that under moderate wind conditions (3–6 m/s), the piezoelectric array generated open-circuit peak voltages in the range of 8–15 V. The regulated output energy was efficiently stored in a 3.7 V, 2200 mAh lithium-ion battery. The stored energy successfully powered low-power electronic loads such as LED indicators and IoT sensing nodes, confirming the system's ability to operate practical devices. Furthermore, the proposed anemokinetics-based energy harvesting system supports SDG 7 and SDG 13, maps to POs 2, 3, 4, 5, 6, 7, and 12, and strengthens PSOs related to embedded systems and green technologies while enhancing SGPA through hands-on experiential learning.

**Keywords:** Anemokinetics, piezoelectric, NodeMCU, Blynk, renewable energy, AVR Microcontroller

## 1. INTRODUCTION

Anemokinetics-Based Power Generation Using Tree Branches with Piezo Strips and NodeMCU for IoT Monitoring.In the pursuit of sustainable and decentralized energy solutions, the utilization of ambient mechanical energy sources has gained significant attention. Among these, anemokinetics the harvesting of energy from wind-induced motion offers a unique, underutilized method for micro-energy generation. Traditional wind turbines and large-scale harvesting systems often require significant infrastructure and consistent wind speeds. However, nature provides an alternative medium for harnessing wind energy: tree branches. Trees naturally oscillate with wind currents, converting wind energy into low-frequency mechanical vibrations, which can be exploited for energy generation at a smaller, localized scale. This project introduces an innovative approach to energy harvesting by leveraging the natural swaying motion of tree branches. It employs piezoelectric strips, which generate electrical charge in response to mechanical stress and strain. When attached to tree branches, these piezo elements convert the kinetic motion induced by wind into electrical voltage. Although the energy harvested per unit is minimal, it is sufficient for powering low-power sensors or recharging small energy storage devices. To make this harvested energy meaningful and measurable, the project integrates an IoT monitoring system using the NodeMCU (ESP8266) microcontroller. The NodeMCU reads the voltage output from the piezoelectric harvesters and transmits real-time data to a cloud-based dashboard (such as Blynk or ThingSpeak). This not only enables remote monitoring of energy generation performance but also allows for data analytics and usage tracking over time.The core idea behind this system is to demonstrate a low-cost, scalable, and environmentally harmonious method of energy harvesting. Unlike photovoltaic or turbine-based systems, this approach blends seamlessly with natural ecosystems, requires minimal maintenance, and avoids any significant visual or structural impact. The concept can be applied in forested or rural areas to power small sensors for environmental monitoring, agricultural automation, or ecological studies where traditional energy infrastructure is not feasible.

In summary, this project combines renewable energy harvesting, piezoelectric technology, and IoT-based monitoring into a cohesive system that represents the future of smart, sustainable, and bio-integrated energy systems. It paves the way for further exploration into biomimetic and ambient energy solutions suited for the Internet of Things era.

## 2. LITERATURE SURVEY

1. **Alam & Yadav (2025)** Flexible piezo strips for hybrid wind–mechanical harvesting. They developed and tested flexible piezo strips (materials and fabrication) for bending-dominant wind/structural motion. Results show improved bandwidth and durability versus rigid ceramics, making these strips suitable for branch-mounted harvesters.
2. **Bakhtiar et al. (2025)** Fluid flow–based vibration energy harvesters: critical review. A systematic review of flow-driven harvesters (VIV, galloping, flutter) covering mechanisms, performance, and limitations. It concludes that flow-structure coupling design rules are essential when adapting aero-elastic concepts to branch geometries.
3. **Chowdhury & Islam (2025)** IoT-integrated self-powered environmental sensors using piezo strips. Designed and prototyped self-powered sensor nodes combining piezo harvesters, conditioning electronics, and IoT communication. Demonstrated feasible duty-cycled sensing with energy budgeting, a direct model for NodeMCU-based IoT systems.
4. **Gazkoo, Sadhu & Liu (2025)** Vibration harvesting in large-scale civil infrastructure: outlook. Comprehensive study on vibration harvesters deployed on bridges and buildings emphasizing robustness and lifecycle. Their lessons on mounting and environmental exposure translate well to long-term, tree-mounted systems.
5. **Ghildiyal et al. (2025)** Electrical phenomena in trees and wood: review. Reviewed intrinsic electrical and ionic behaviors in plant tissues and wood. The study highlights limited power densities but suggests potential for complementary bioelectric hybrid systems.
6. **Greenman et al. (2025)** Energy harvesting from plants using hybrid microbial fuel cells. Explored plant-MFC hybrids with prototypes and application scenarios. Found that continuous baseline power is possible, useful as an auxiliary energy source for smoothing intermittent mechanical harvesting.
7. **Guo et al. (2025)** Leaf-based harvesting and storage using hygroscopic iron hydrogel. Demonstrated a humidity-driven, leaf-inspired device that both harvests and stores energy. Achieved continuous output in laboratory tests, inspiring hybrid storage or continuous-supply modules for field nodes.
8. **Huang & Wang (2025)** Modeling of tree-inspired piezoelectric systems. Presented FEM and analytical models coupling branch dynamics with piezo transducers. Showed how branch stiffness, mass, and excitation spectrum determine optimal transducer sizing and expected power generation.
9. **Khan & Malik (2025)** Tree motion-induced piezoelectric generators: a review. Reviewed piezoelectric generation from tree sway with various designs and tuning strategies. Emphasized mounting position and resonance tuning as critical factors for efficient branch-based harvesting.
10. **Kumar & Patel (2025)** Smart piezoelectric wind energy harvesting with IoT monitoring. Developed a prototype combining piezo harvesters with IoT-based real-time telemetry. Demonstrated that remote monitoring improves maintenance and overall energy management.
11. **Litak et al. (2025)** Aero-elastic resonator: effect of bluff body diameter. Conducted a wind-tunnel study showing how bluff-body geometry affects vortex-induced performance and resonance locking. Suggested aero-elastic augmentation can significantly increase harvested energy.
12. **Mehta & Das (2025)** Piezoelectric transducer-based scavenging: modern approach. Reviewed piezo transducer designs, impedance matching, and storage circuits. Highlighted that efficient conditioning circuits (MPPT, rectifiers) are as important as mechanical design.
13. **Moslemi et al. (2025)** Advancements in vibration harvesting for bridges: systematic review. Studied bridge-mounted harvesters focusing on scaling, durability, and performance. Shared transferable insights on rugged mounting and outdoor node monitoring strategies.
14. **Omidvarnia & Sarhadi (2025)** Nature-inspired designs in wind energy: review. Surveyed biomimetic wind-energy concepts and their performance advantages. Encouraged use of natural shapes and compliant mechanisms for improved efficiency and durability.
15. **Parashar et al. (2025)** ML-driven, triboelectric wearable sensing. Demonstrated triboelectric nanogenerators (TEGs) combined with machine learning for gait sensing. Showed how harvested-signal characteristics can be used for sensing while conserving energy.
16. **Rahman et al. (2025)** Energy harvesting from living plants: review and way forward. Reviewed plant-based harvesting approaches (bioelectric, MFCs, mechanical). Concluded that hybrid architectures offer better reliability and sustainability for real-world use.
17. **Reddy & Raj (2025)** Wireless monitoring of micro-power generation using NodeMCU. Developed firmware and telemetry for NodeMCU-based micro-harvesters. Shared practical lessons on buffering, power-fail safety, and minimal transmission schedules.
18. **Simone et al. (2025)** Quantifying benefits of hybrid harvesting from natural sources. Presented analytical models showing that hybridizing multiple sources increases availability. Supported combining piezoelectric, bioelectric, and storage-based systems for reliability.
19. **Singh & Arora (2025)** IoT-enabled vibration-based power generation for smart cities. Surveyed vibration harvesters used for powering urban IoT networks. Provided scale-up insights relevant for multi-tree sensor systems.

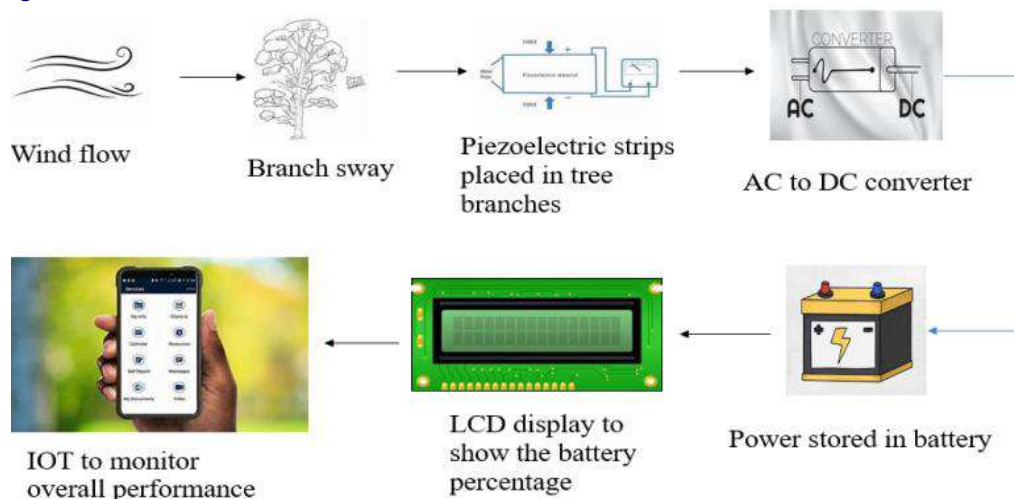
20. **Tariq & Bashir (2025)** Low-cost harvesting for rural IoT using piezo bending. Presented low-cost piezo prototypes tested in rural contexts. Demonstrated that affordable strips and duty-cycling can sustain telemetry for basic IoT nodes.
21. **Trinh & Chung (2025)** Advanced triboelectric nanogenerators: review. Reviewed TENG mechanisms and materials suitable for low-frequency motion. Highlighted their high voltage but low current output characteristics, useful for large branch displacements.
22. **Xu et al. (2025)** Integrating machine learning with TENGs: optimizing materials and doping. Combined ML algorithms with experiments to optimize TENG electrode materials. Showed ML can accelerate transducer improvement when many design variables exist.
23. **Yu & Li (2025)** Maple leaf-based TENG for sports monitoring. Built a bio-inspired, leaf-shaped TENG for motion sensing in sports. Demonstrated efficient mechanical-to-electrical conversion using natural geometries.
24. **Zhang et al. (2025)** Rotational TENG with ML for speed monitoring. Presented a rotational TENG with an ML model for accurate speed estimation. Highlighted dual functionality as a power source and sensor for smart IoT applications.
25. **Zhang, Li & Wang et al. (2025)** Review of electromagnetic wind harvesters based on flow-induced vibrations. Comprehensive review comparing electromagnetic, piezoelectric, and TENG harvesters. Concluded EM harvesters suit higher-mass applications but are heavier, aiding hybrid design decisions.

### 3. PROPOSED SYSTEM

#### 3.1 INTRODUCTION

This system presents a smart wind energy harvesting approach using piezoelectric technology integrated with IoT monitoring. When wind flows, tree branches naturally sway, and piezoelectric strips placed inside the branches convert this mechanical vibration into electrical energy. The generated AC power is then converted into DC using an AC-to-DC converter and stored in a rechargeable battery. An LCD display shows the battery charge percentage for real-time local monitoring, while an IoT platform enables remote tracking of overall system performance. This design offers a sustainable, low-cost, and eco-friendly solution for generating small-scale renewable energy from natural environmental movements.

#### 3.2 Block Diagram



**Fig 3.1** Proposed block Diagram

At the initial stage of the system, before wind energy harvesting begins, the battery contains a certain amount of stored energy based on its previous usage condition. When the system is switched on, the microcontroller first performs a voltage sensing operation to measure the exact battery level. For example, if a 12V rechargeable battery is used, it may not be fully charged at the beginning. Assume that the initial measured voltage is 10.8V. This voltage indicates that the battery is partially charged, approximately around 60% of its full capacity. The microcontroller reads this voltage through an analog input using a voltage divider circuit to ensure safe measurement. Immediately after sensing, this initial value is processed and sent to the LCD display. The LCD then shows the message "Battery Voltage: 10.8V" or "Battery Level: 60%," clearly indicating the starting condition of the battery before any new energy generation takes place. Once the initial reading is displayed, the energy harvesting process begins when wind flows across the tree. Due to the wind force, the tree branches start to sway back and forth. The piezoelectric strips that are firmly attached to the branches experience mechanical deformation such as bending, compression, and vibration. According to the piezoelectric principle, whenever mechanical stress is applied to the material, it produces an electrical output. As the branch movement continues, small alternating voltage signals are generated by the piezoelectric strips. The magnitude of this generated voltage depends on factors such as wind speed, frequency of vibration, and the number of piezoelectric strips connected in the system. The electrical output produced by the piezoelectric strips is in the form of low-level alternating current (AC). Since batteries require direct current (DC) for charging, this AC signal is passed through an AC to DC converter circuit. The converter typically consists of a rectifier and filter components that convert the fluctuating AC signal into a smoother DC voltage. After conversion, the DC output becomes suitable for charging the battery.

This DC energy is then supplied to the battery terminals, gradually increasing the stored charge. As the charging process continues over time, the battery voltage slowly rises. For instance, after several minutes of steady wind flow, the battery voltage may increase from 10.8V to 11.1V. The microcontroller continuously monitors the battery voltage at regular intervals, such as every few seconds. When it detects the updated voltage, it refreshes the LCD display with the new value. The screen may now show “Battery Voltage: 11.1V” or “Battery Level: 63%.” This indicates that additional energy has been successfully harvested and stored in the battery. If the wind intensity increases, the branch movement becomes stronger, causing greater mechanical stress on the piezoelectric strips. As a result, a higher electrical output is generated, leading to faster charging of the battery. Under favorable wind conditions, the battery voltage may further increase to 11.8V or even 12.4V, which is close to the full-charge level of a 12V battery. At this stage, the LCD display updates again to show “Battery Voltage: 12.4V” or “Battery Level: 95%.” This continuous monitoring and display mechanism allows the user to clearly observe the difference between the initial battery reading and the final charged value. Therefore, the system operates in a continuous cycle where the initial battery voltage is first measured and displayed, followed by wind-induced energy generation, AC to DC conversion, battery charging, and real-time voltage updating on the LCD. By comparing the starting voltage (10.8V) with the final voltage (for example, 12.4V), the total energy generated during the wind exposure period can be analyzed. This detailed monitoring process ensures accurate performance evaluation of the piezoelectric tree energy harvesting system.

**Table 3.1** Output Table Based on Wind Speed Range:

S.No	Wind Speed Range (m/s)	Branch Vibration Level	Piezo Output Voltage (V Peak)	Rectified DC Voltage (V)	Battery Voltage (V)	Website Status
1	0 – 1	Very Low	0 – 1 V	0 – 0.5 V	3.50 V	No Output / Idle
2	1 – 2	Low	1 – 3 V	0.8 – 1.5 V	3.52 V	Low Update
3	2 – 3	Low-Medium	3 – 5 V	1.5 – 2.5 V	3.55 V	Low Data
4	3 – 4	Medium	5 – 7 V	2.5 – 3.5 V	3.60 V	Normal Update
5	4 – 5	Medium-High	7 – 10 V	3.5 – 4.5 V	3.70 V	Stable Monitoring
6	5 – 6	High	10 – 13 V	5 V (Regulated)	3.85 V	Charging Data
7	6 – 7	Very High	13 – 16 V	5 V (Regulated)	4.00 V	Fast Update
8	Above 7	Maximum	16 – 20 V	5 V (Regulated)	4.20 V	High Output Log

### 3.3 APPLICATIONS

The proposed anemokinetics-based power generation system using tree branch vibrations has a wide range of practical applications, especially in areas where conventional electricity supply is unavailable or difficult to implement. Since the system generates micro-level power using piezoelectric strips, it is best suited for low-power electronic devices and IoT-based applications. The integration of NodeMCU and web-based monitoring makes the system intelligent and suitable for real-time remote observation. One of the major applications of this system is in agriculture and smart farming. In rural agricultural fields, farmers require continuous monitoring of soil moisture, temperature, humidity, and water level. Many of these monitoring systems depend on batteries, which need regular replacement. By using tree branch energy harvesting, this system can provide continuous micro-power for small IoT sensors used in irrigation monitoring, crop growth analysis, and greenhouse automation. This reduces dependency on manual battery charging and supports sustainable farming practices. Another important application is in forest and wildlife monitoring systems. Forest areas often lack proper electricity supply, and it is difficult to install solar panels or wind turbines due to space and environmental restrictions. This proposed system can be installed on trees without disturbing the natural environment. It can be used to power sensors that measure environmental parameters such as air quality, temperature, rainfall, humidity, and wind speed. It can also support wildlife tracking devices and forest fire detection sensors, which require continuous low-power operation. The system is also useful in remote IoT sensor networks. Many IoT devices are deployed in distant locations for monitoring water pipelines, weather stations, and agricultural lands. These devices require power for data transmission and sensing. The proposed system provides a decentralized energy source and can act as a backup power supply for IoT nodes, ensuring continuous operation. In smart city and public park monitoring, this system can be implemented in trees located in parks and roadside environments. It can generate power to support small LED lighting, public environmental monitoring sensors, and smart security sensor units. Since it does not require large structures, it is visually clean and environmentally friendly. Another significant application is in disaster management and emergency power supply. During floods, storms, or power failures, small-scale energy generation systems become useful for emergency sensors and communication modules. This system can provide micro-power for emergency indicator lights, warning systems, or data transmission devices. Additionally, the proposed system is useful in educational and research applications. It can be used in engineering colleges and research institutions as a demonstration model for renewable energy harvesting, piezoelectric technology, and IoT integration. It helps students understand real-time energy conversion and monitoring. Overall, this project is best suited for low-power, sustainable, and eco-friendly applications. It provides a practical solution for powering small IoT devices and sensors in rural, forest, and outdoor environments, supporting the future development of green energy and smart monitoring systems.

## 4. SYSTEM REQUIREMENTS

### 4.1 INTRODUCTION:

The hardware part of the proposed system plays a major role in converting wind-induced tree branch motion into usable electrical energy.

This project is based on anemokinetics energy harvesting, where mechanical vibrations produced by the swaying of tree branches are captured and converted into electrical voltage using piezoelectric strips. The hardware setup is designed to be low-cost, compact, and suitable for outdoor environments such as rural areas, forests, and agricultural lands. The main hardware components include piezoelectric strips, rectifier circuit, filter capacitors, voltage regulator, battery storage unit, and NodeMCU (ESP8266) microcontroller for IoT monitoring. Piezoelectric strips act as the energy harvesting sensors and generate alternating voltage when pressure or vibration is applied. Since the generated voltage is irregular and AC in nature, a bridge rectifier circuit is used to convert it into DC voltage. Capacitors are used to reduce fluctuations and provide smooth DC output. To store the harvested energy, a rechargeable lithium-ion battery (3.7V, 2200mAh) is used along with a charging module for safe charging. The stored energy can be utilized for low-power loads such as LED lighting, sensor nodes, and IoT devices. For monitoring and data transmission, NodeMCU is used due to its built-in Wi-Fi feature. It measures the output voltage and sends real-time data to a web-based monitoring platform, allowing remote monitoring and analysis. Thus, the hardware system combines energy harvesting, power conditioning, energy storage, and IoT communication to provide a sustainable and smart renewable power generation solution.

## 4.2 HARDWARE COMPONENTS

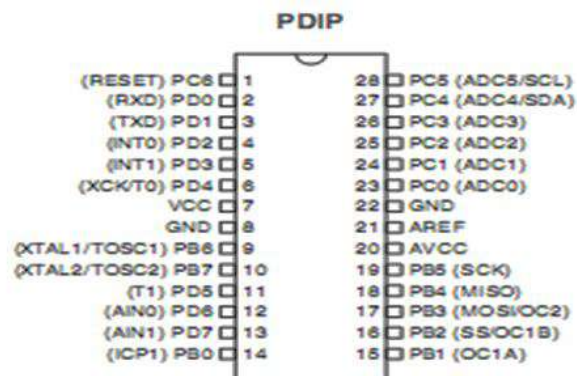
### 4.2.1 Esp8266 Microcontroller:

The NodeMCU board is a development board based on the ESP8266 WiFi microcontroller developed by Espressif Systems. It operates at 3.3V and can be powered using 5V through a USB connection. This module is mainly used to provide wireless communication in the system. It connects the project to WiFi and allows data monitoring and control through a web page, usually accessed through a local IP address such as 192.168.4.1. In this project, it acts as the main controller and communication unit, sending data to a mobile device. The ESP8266 Wi-Fi module is a low-cost microcontroller with built-in Wi-Fi capability, widely used for IoT monitoring and wireless communication applications. Developed by Espressif Systems, the ESP8266 integrates a TCP/IP protocol stack, allowing it to connect directly to a Wi-Fi network and communicate with cloud servers. In an anemokinetics-based energy harvesting system, the ESP8266 collects data such as voltage, current, and power generated from the piezoelectric setup and transmits this information to cloud platforms for real-time monitoring. It can be programmed using the Arduino IDE and supports communication protocols like HTTP and MQTT. Due to its low power consumption, compact size, and reliable wireless connectivity, the ESP8266 is highly suitable for remote energy monitoring and smart IoT applications.

#### Features

- High-performance, Low-power AVR 8-bit Microcontroller
- Advanced RISC Architecture:
  - 130 Powerful Instructions
  - Most Single-clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Up to 16 MIPS Throughput at 16 MHz
  - On-chip 2-cycle Multiplier
- High Endurance Non-volatile Memory segments:
  - 8K Bytes of In-System Self-programmable Flash program memory
  - 512 Bytes EEPROM
  - 1K Byte Internal SRAM
  - Write/Erase Cycles: 10,000 Flash/100,000 EEPROM
  - Data retention: 20 years at 85°C/100 years at 25°C
  - Optional Boot Code Section with Independent Lock Bits
- In-System Programming by On-chip Boot Program
  - True Read-While-Write Operation
- #Programming Lock for Software Security
- Peripheral Features:
  - Two 8-bit Timer/Counters with Separate Prescaler, one Compare Mode
  - One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Cap Mode
  - Real Time Counter with Separate Oscillator
  - Three PWM Channels
  - 8-channel ADC in TQFP and QFN/MLF package *Eight Channels 10-bit Accuracy*
  - 6-channel ADC in PDIP package
- Six Channels 10-bit Accuracy:
  - Byte-oriented Two-wire Serial Interface
  - Programmable Serial USART
  - Master/Slave SPI Serial Interface
  - Programmable Watchdog Timer with Separate On-chip Oscillator
  - On-chip Analog Comparator
- Special Microcontroller Features:
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated RC Oscillator

- External and Internal Interrupt Sources
- Five Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, an Standby
- I/O and Packages:
  - 23 Programmable I/O Lines
  - 28-lead PDIP, 32-lead TQFP, and 32-pad QFN/MLF
- Operating Voltages:
  - 2.7 - 5.5V (ESP8266L)
  - 4.5 - 5.5V (ESP8266)
- Speed Grades:
  - 0 - 8 MHz (ESP8266L)
  - 0 - 16 MHz (ESP8266)
- Power Consumption at 4 Mhz, 3V, 25°C:
  - Active: 3.6 mA
  - Idle Mode: 1.0 mA
  - Power-down Mode: 0.5  $\mu$ A

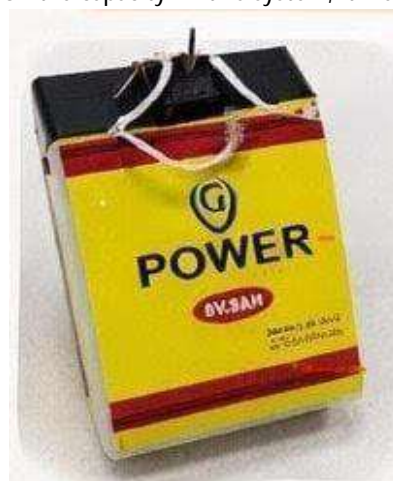


**Fig 4.1 Pin Configuration**

The ESP8266 is described as a low-power 8-bit AVR RISC microcontroller designed for efficient and flexible embedded applications. It can achieve performance close to 1 MIPS per MHz by executing most instructions in a single clock cycle, thanks to its 32 general-purpose registers directly connected to the ALU. The device includes 8KB of in-system programmable Flash memory with Read-While-Write capability, 512 bytes of EEPROM, and 1KB of SRAM. It also provides 23 GPIO pins, three Timer/Counters, internal and external interrupts, USART, SPI, Two-Wire Interface (I<sup>2</sup>C), a 10-bit multi-channel ADC, and a programmable watchdog timer. In addition, the microcontroller supports five power-saving modes Idle, Power-down, Power-save, ADC Noise Reduction, and Standby allowing designers to balance power consumption and performance. It can be reprogrammed in-system through SPI or an on-chip boot loader, making it highly suitable for cost-effective, low-power embedded control systems.

#### 4.2.2 Battery:

12V 4.5Ah Battery (COBRAS – Sealed Lead Acid) .The black battery shown in the image is a 12V, 4.5Ah Sealed Lead Acid (SLA) battery manufactured under the brand COBRAS. The total energy storage capacity of this battery is 54 Wh (12V × 4.5Ah). This means it can supply 54 watts for one hour, or a 10W load for approximately 5 hours. It is used to store the harvested energy and supply power to the load when required.6V 5Ah Yellow Battery (VRLA).The yellow battery is a 6V, 5Ah VRLA (Valve Regulated Lead Acid) battery. It is commonly used in small backup systems. It stores electrical energy and can supply moderate loads depending on the capacity. In this system, it may be used as an additional storage unit.



**Fig 4.2 Battery (6 V)**

A two lithium battery utilized with the range of 12 V, 2200 mAh is a compact and lightweight rechargeable power source widely used in portable electronics, embedded systems, medical devices, security systems, and small UPS applications. It is usually made of three lithium-ion cells connected in series, giving a nominal voltage of 11.1V and a fully charged voltage of 12.6V. With a capacity of 2200mAh (2.2Ah), the battery can store about 26.4 watt-hours of energy, meaning it can supply 1 ampere of current for approximately 2.2 hours under ideal conditions. Compared to traditional 12V lead-acid batteries, lithium batteries are smaller, lighter, more efficient, and have a longer cycle life, often lasting 300 to 1000 charge cycles or more. They also feature low self-discharge, allowing them to retain charge for longer periods when not in use. Most 12V lithium battery packs include a built-in Battery Management System (BMS) that protects against overcharging, deep discharge, over current, and short circuits, ensuring safety and extending battery life. Proper charging using a compatible 12.6V lithium charger is essential for safe and optimal performance.

#### 4.2.3 DC-AC Converter:

The SMPS (Switched Mode Power Supply) board is used to convert AC voltage into DC voltage. In this system, it converts 230V AC input into 12V DC output. The transformer label indicates 12V, 10W output capacity. This power supply provides the required DC voltage to operate components like the relay, LED lights, and battery charging circuit. It ensures stable and efficient power conversion.



Fig 4.3 DC-AC Converter

In our project, the batteries store energy in the form of DC voltage. A single lithium-ion battery provides 3.7V nominal voltage (maximum 4.2V when fully charged). If two batteries are connected in series, the total voltage becomes 7.4V nominal (8.4V fully charged). However, this stored energy is direct current (DC). If we want to operate AC appliances such as 230V AC loads, then a DC to AC conversion circuit called an inverter is required. The inverter converts low-voltage DC from the battery into alternating current (AC). First, the DC voltage from the battery is passed into an oscillator circuit that generates a high-frequency switching signal. This switching is usually done using MOSFETs or transistors. The switching circuit rapidly turns the DC on and off, creating a square wave AC signal. This AC signal is then passed through a step-up transformer to increase the voltage level. For example, if the battery provides 12V DC (after boosting), the transformer can step it up to 230V AC. So the inverter performs two main operations: DC switching and voltage stepping. In our case, if the battery voltage is only 3.7V or 7.4V, first a DC-DC boost converter is needed to increase the voltage to 12V DC. Then that 12V DC is given to an inverter circuit, which converts it into 230V AC using a transformer. The output AC voltage can be around 110V or 230V depending on the transformer design. However, the current capability depends on battery capacity and inverter rating. Since our battery is 2200mAh, it can only support small AC loads for a limited time. It is important to note that inverter circuits introduce power loss due to switching and transformer losses. Efficiency is usually around 70% to 90% depending on design. Therefore, for micro-energy harvesting systems like ours, DC loads such as LED lights are more efficient than converting to AC.

#### 4.2.4 Relay:

The relay module is a 1-channel electromagnetic switching device. It operates with a 5V coil voltage and can switch higher voltages such as 230V AC or 12V DC loads. In this project, the relay is controlled by the NodeMCU to turn the load (LED bulb) ON and OFF. It acts as an electrical isolation device between the low-power control circuit and the high-power load circuit. The relay used in this project acts as an electrically operated switch that allows the low-voltage NodeMCU controller to control higher voltage loads such as LED lights or street lighting systems. Since the NodeMCU operates at 3.3V logic level and cannot directly handle higher current loads, the relay is used as an intermediate switching device. When the NodeMCU sends a control signal to the relay module, the relay coil gets activated (usually 5V coil voltage in most project modules). Once activated, the relay closes its internal contacts and allows the battery voltage to flow to the load. When the control signal is turned OFF, the relay opens the circuit and disconnects the load from the battery. In this system, the relay does not increase or decrease voltage; it only acts as a switch. If the batteries are connected in parallel, the output voltage will be 3.7V and the same 3.7V will be supplied to the LED through the relay. If the batteries are connected in series, the output voltage becomes 7.4V and that same voltage will pass through the relay to the load. The relay typically supports higher ratings such as 10A at 30V DC, which is more than sufficient for low-power LED lighting systems. Thus, the relay ensures safe isolation between the control circuit and the load circuit while enabling automatic switching of the lighting system.



Fig 4.4 Relay

#### 4.2.5 Piezoelectric Strips:

The piezoelectric discs are energy harvesting components. When mechanical pressure or vibration is applied, they generate a small AC voltage due to the piezoelectric effect. In this project, they are used to convert mechanical vibrations into electrical energy. The generated voltage is then stored in the battery after proper rectification and regulation.

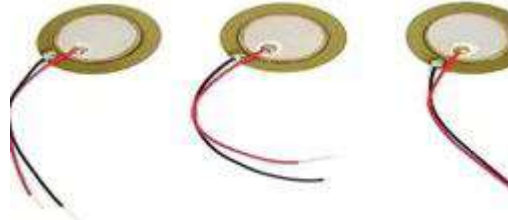


Fig 4.5 Piezoelectric Strips

In this project, piezoelectric strips are used to convert wind-induced mechanical vibration into electrical energy. Each strip contains ten piezoelectric coins, and there are three strips in total, making thirty coins. The main function of each piezo coin is to generate electrical voltage when mechanical stress or bending is applied to it. When the tree branch sways due to wind, the strip bends continuously, and this bending creates alternating electrical voltage because of the piezoelectric effect. Under small vibration, one piezo coin can generate around 1V to 3V peak AC voltage. Under moderate wind conditions, one coin can produce approximately 5V to 10V peak AC, and during strong bending it may reach up to 15V peak in open-circuit condition. Since each strip has ten coins, if they are connected in series inside the strip, the voltage adds together. That means one strip can generate around 20V to 30V under small wind, 30V to 60V under moderate wind, and up to 80V or more peak during strong vibration. If the coins are connected in parallel, the voltage remains similar to one coin, but the current increases. Because three such strips are used in the system, the total output further depends on whether the strips are connected in series or parallel. Even though the voltage values may appear high, the current produced by piezo elements is very low, so continuous vibration is required to obtain usable power. Thus, the piezo strips function as vibration-based energy converters that transform natural wind motion into electrical voltage without using any rotating mechanical parts.

#### 4.2.6 Rectifier:

A bridge rectifier circuit is an essential stage in a piezoelectric energy harvesting system because the electrical output from piezo strips is naturally alternating (AC) and varies with vibration intensity. When wind moves the tree branches, the piezo strips bend back and forth, producing voltage that alternates between positive and negative cycles. This alternating signal cannot directly charge a battery or power microcontrollers like the ESP8266, as they require stable DC input.

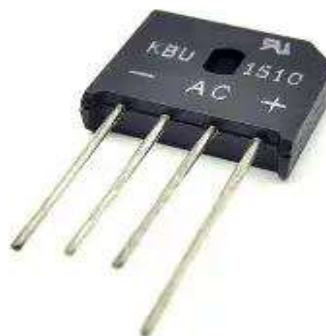


Fig 4.6 Rectifier

The bridge rectifier, made of four diodes arranged in a closed-loop bridge configuration, ensures that during both halves of the AC cycle, current flows in the same direction through the load. This results in full-wave rectification, improving energy utilization compared to half-wave rectifiers. In low-power systems, diode selection is very important. Standard silicon diodes have a forward voltage drop of about 0.7V, which can significantly reduce the small voltage generated by piezo strips. Therefore, Schottky diodes, which have a lower forward voltage drop (around 0.2–0.3V), are often used to improve efficiency. After rectification, the output is pulsating DC with ripples, so a smoothing capacitor is added to reduce fluctuations. In some designs, a DC-DC boost converter may also be included to increase the voltage to a usable level. Overall, the bridge rectifier ensures efficient conversion of irregular AC signals from mechanical vibrations into usable DC power for storage and IoT-based monitoring systems.

#### 4.2.7 Filter Capacitor:

A filter capacitor is an electronic component used to smooth the pulsating DC output from a rectifier circuit. After a bridge rectifier converts AC voltage (from piezoelectric strips) into DC, the output is not perfectly steady; it contains ripples or fluctuations. The filter capacitor is connected across the rectifier output to reduce these voltage variations and provide a more stable DC supply.



Fig 4.7 Filter Capacitor

The filter capacitor is used after the rectifier to smooth the pulsating DC voltage. When the bridge rectifier converts AC into DC, the output is not pure DC; it is pulsating DC with ripple, meaning the voltage continuously rises and falls. The filter capacitor reduces this fluctuation. It works by charging when the rectified voltage increases and discharging when the voltage drops. This charging and discharging action fills the gaps in the waveform and makes the output more stable. For example, if the rectified output is around 20V peak with ripple, the capacitor stores charge near the peak level and maintains the voltage closer to that value instead of letting it drop to zero between cycles. However, the capacitor does not increase voltage; it only smooths it. The voltage across the capacitor will be approximately equal to the peak rectified voltage minus diode drops. The amount of ripple reduction depends on the capacitor value and load current. Larger capacitance (like 470 $\mu$ F to 1000 $\mu$ F or higher depending on design) results in less ripple and more stable DC output. If the load current increases, ripple also increases unless a higher-value capacitor is used. Therefore, the main function of the filter capacitor is to reduce ripple voltage, stabilize the DC level, and improve overall power quality in the system.

#### 4.2.8 Supporting Components:

Supporting components such as resistors, diodes, PCB board, connecting wires, mounting brackets, and a protective enclosure play an essential role in ensuring the proper functioning and durability of the system. Resistors are used for current limiting, voltage division, and signal conditioning to protect sensitive components like the ESP8266. Diodes are used for rectification, reverse polarity protection, and preventing backflow of current from the battery to the piezo strips. A well-designed PCB (Printed Circuit Board) provides stable mounting for electronic components, reduces noise, and ensures reliable electrical connections. Connecting wires transmit power and signals between different stages of the circuit and must be properly insulated to prevent losses or short circuits. Mounting brackets securely attach piezo strips to tree branches while allowing sufficient flexibility for vibration. Finally, a protective enclosure shields the entire circuit from environmental factors such as rain, dust, humidity, and temperature changes, ensuring long-term outdoor operation and system reliability.

### 4.3 SOFTWARE COMPONENTS

#### 4.3.1 Introduction

The software requirements define the programs, tools, and platforms needed to develop, program, and monitor the innovative anemokinetics-based free energy system using the ESP8266. The software plays a crucial role in controlling data acquisition, processing sensor values, managing power monitoring, and transmitting real-time information to cloud platforms through Wi-Fi. To program the ESP8266, development environments such as Arduino IDE or other compatible firmware platforms are used. The software includes embedded code for reading voltage and current sensor data, processing analog signals, and sending the collected data to IoT dashboards or mobile applications. Communication protocols such as HTTP or MQTT are commonly implemented for cloud connectivity. Additionally, IoT cloud platforms are required for data visualization, storage, and remote monitoring.

The software system ensures accurate measurement, efficient data transmission, and reliable monitoring of the harvested energy, making it an essential part of the overall renewable energy solution.

#### 4.3.2 CodeVision AVR

CodeVisionAVR is an Integrated Development Environment (IDE) and C compiler used for programming AVR microcontrollers. It supports Embedded C and provides automatic code generation for peripherals such as ADC, timers, UART, SPI, CodeVision AVR is an Integrated Development Environment (IDE) and C compiler used for programming AVR microcontrollers. It supports Embedded C and provides automatic code generation for peripherals such as ADC, timers, UART, SPI, and I2C. The software includes debugging and simulation tools that simplify program testing and verification. Its automatic initialization feature reduces coding complexity and development time. Due to its efficiency and user-friendly interface, CodeVisionAVR is widely used in academic and industrial embedded system projects

#### 4.3.3 AVR Microcontroller Architecture

The AVR microcontroller family was developed by Atmel and is based on an 8-bit RISC architecture. It follows a Modified Harvard Architecture, where program memory and data memory are separated to improve performance.

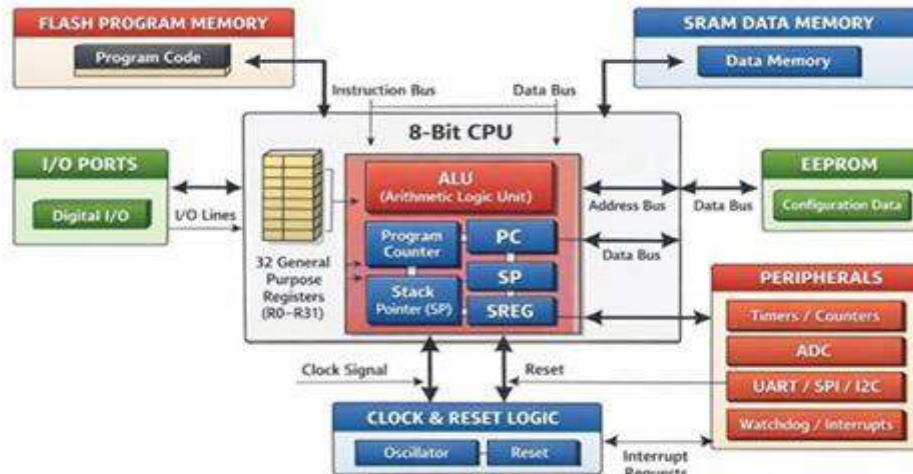


Fig 4.8 AVR Microcontroller Architecture

The architecture includes 32 general-purpose registers directly connected to the Arithmetic Logic Unit (ALU), allowing most instructions to execute in a single clock cycle. AVR microcontrollers integrate Flash memory for program storage, SRAM for temporary data storage, and EEPROM for non-volatile data retention. They also include built-in peripherals such as timers, ADC, UART, SPI, I2C, watchdog timers, and power-saving modes. These features make AVR microcontrollers suitable for efficient and low-power embedded system applications.

#### 4.3.4 Hardware Platform (NodeMCU – ESP Based)

The proposed system uses a NodeMCU development board based on either ESP8266 or ESP32. These microcontrollers provide built-in Wi-Fi connectivity, making them suitable for IoT-based monitoring applications. The energy harvested from tree branch vibrations is regulated and supplied to the microcontroller through a voltage divider and power management circuit. Environmental sensors and vibration sensors are interfaced through ADC or I2C communication protocols. The regulated 3.3V supply powers the entire system.



Fig 4.9 NodeMCU ESP8266

The NodeMCU development board is based on the ESP8266 developed by Espressif Systems. It is widely used in Internet of Things (IoT) applications because it has an inbuilt Wi-Fi module and can directly connect to the internet. The ESP8266 acts as the main controller of the board, executing the program and handling communication tasks. It contains a 32-bit processor, internal memory, and a built-in TCP/IP stack for wireless communication. The board is powered using a Micro USB connector, which is also used to upload programs from a computer. A USB-to-Serial converter (CP2102) is present on the board to convert USB signals into serial communication, enabling programming and serial monitoring. Since the ESP8266 operates at 3.3V, a voltage regulator is included to convert the 5V supply from the USB into a stable 3.3V output. A power LED indicates whether the board is receiving power.

The NodeMCU provides multiple GPIO (General Purpose Input/ Output) pins labeled D0 to D8, which can be used to interface sensors, LEDs, relays, motors, and other electronic components. It also includes one analog input pin (A0) that can read analog voltage signals. Additionally, the board supports communication protocols such as UART, SPI, and I2C for connecting external devices and modules. There are two important buttons on the board: the Reset button and the Flash button. The Reset button restarts the microcontroller, while the Flash button is used to enter programming mode during code uploading. Overall, the NodeMCU hardware platform is compact, low-cost, and efficient, making it suitable for wireless embedded system and IoT projects.

#### 4.3.5 System Software Logic

The system software operates based on an energy-aware control mechanism. During startup, the microcontroller initializes all peripherals and checks the available stored energy using the ADC. If the energy level is below a predefined threshold, the system software operates based on an energy-aware control mechanism. During startup, the microcontroller initializes all peripherals and checks the available stored energy using the ADC. If the energy level is below a predefined threshold, the system enters deep sleep mode to conserve power. When sufficient energy is available, the system performs sensing operations such as voltage measurement and vibration analysis. The collected data is processed and formatted into a structured payload. The system then attempts to establish a Wi-Fi connection and transmit the data to the cloud server using MQTT or HTTP protocols. If the connection fails, the data is stored locally and transmitted later when connectivity is restored. After transmission, the system returns to sleep mode based on energy availability to ensure efficient power management.

#### 4.3.6 Software Implementation

The software is developed using the Arduino IDE environment. The program is structured into modular files for energy management, sensor reading, communication handling, and data storage. Important parameters such as minimum sleep voltage and transmission threshold voltage are defined in configuration files. A power-aware transmission logic is implemented to adjust sensing and communication frequency based on available energy. This ensures reliable operation under intermittent energy conditions while maximizing data delivery efficiency.

#### 4.3.7 Software Testing

The software is validated through unit testing and integration testing. Unit testing verifies ADC scaling, data formatting, and buffering mechanisms. Integration testing is performed using a local MQTT broker such as Mosquitto to confirm end-to-end communication between the device and the server. Performance metrics such as energy consumption per transmission, successful data delivery rate, and system uptime are analyzed to ensure system reliability.

### 5. RESULTS AND DISCUSSION

This Project presents the detailed results obtained from the simulation and hardware implementation of the proposed vibration-based energy harvesting system integrated with IoT monitoring. The system performance was carefully analyzed in three stages, namely simulation using Proteus software, practical hardware execution, and real-time monitoring using the ESP8266 Wi-Fi module. The objective of this chapter is to evaluate the effectiveness, reliability, and practical feasibility of the proposed system by comparing theoretical expectations with actual experimental outcomes.

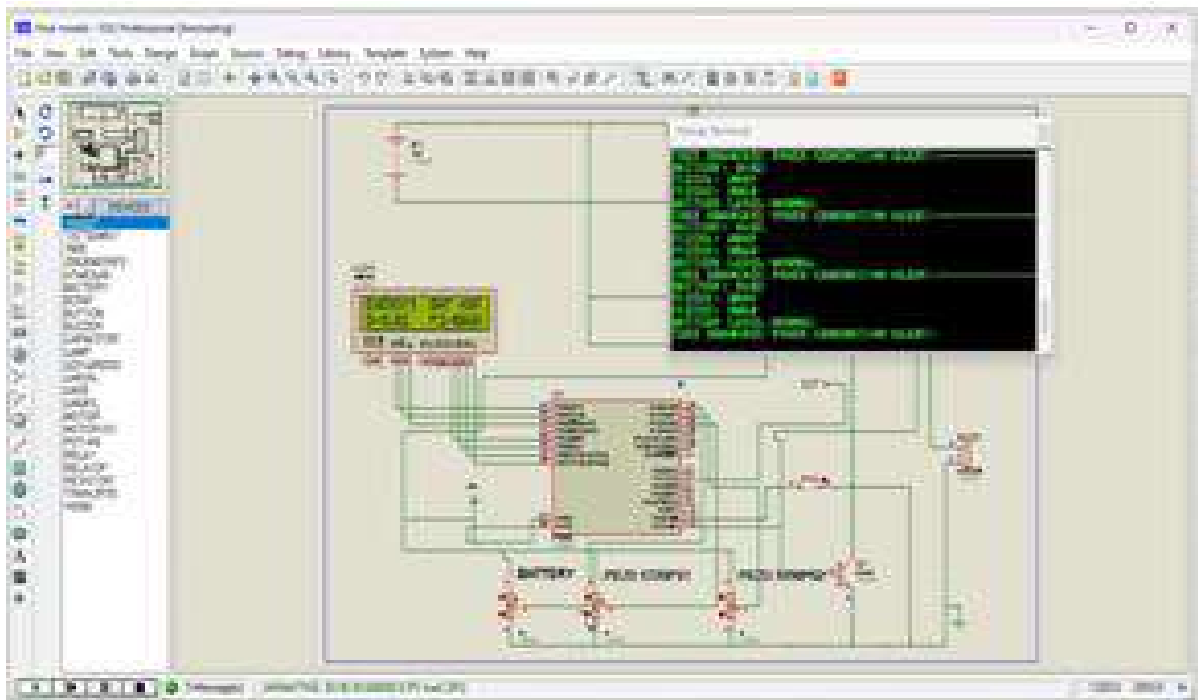
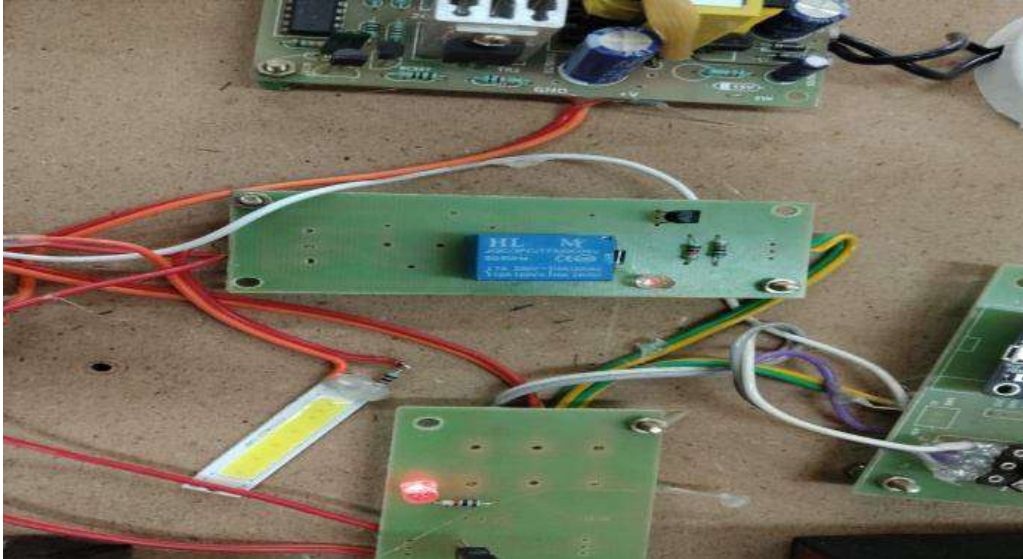


Fig 5.1 Simulation results

The initial verification of the proposed system was carried out using Proteus simulation software. The complete circuit was designed by incorporating an AC voltage source to represent the output of the piezoelectric sensor under vibration conditions. When the simulation was executed, the AC waveform was observed as a sinusoidal signal.

After passing through the bridge rectifier circuit, the output waveform changed into pulsating DC, which confirmed proper rectification of the input signal. A filter capacitor was then included in the circuit to reduce ripple voltage, and the waveform became smoother and more stable. The addition of a voltage regulator ensured that the output voltage remained constant even when variations were introduced in the input AC source. The regulated DC voltage was observed to maintain a steady level suitable for powering electronic components. The microcontroller was programmed and tested within the simulation environment, and the analog voltage readings were successfully displayed in the virtual terminal window. The simulation results closely matched the expected theoretical behavior, thereby validating the correctness of the circuit design and confirming that the system was ready for hardware implementation.



**Fig 5.2** Energy Conversion and Power Conditioning Section

The internal hardware modules responsible for energy conversion and battery charging. This section includes the piezoelectric input terminals, bridge rectifier circuit, filtering capacitors, voltage regulation components, relay module, LED indicators, and connection wires. When mechanical vibration is applied to the piezoelectric discs, an alternating voltage is generated due to the piezoelectric effect. However, this generated voltage is irregular, low in magnitude, and in AC form. Therefore, direct battery charging is not possible at this stage. The AC output from the piezoelectric array is fed into a bridge rectifier circuit. The rectifier converts the alternating waveform into pulsating DC voltage. After rectification, filtering capacitors are used to smooth the pulsations and reduce voltage fluctuations. This produces a relatively stable DC output suitable for charging the rechargeable battery. Before initiating vibration testing, the battery voltage was measured using a voltage sensing circuit connected to the microcontroller. The initial battery voltage was approximately 5.4V (for a 6V battery system), indicating a partially charged state. Once vibration was applied, the LED indicator on the charging circuit began to glow, confirming active energy transfer. The DC output was then supplied to the battery terminals, gradually increasing the stored charge. This stage verifies that the system successfully converts mechanical vibration into usable electrical energy. The IoT-based web monitoring interface accessed through a mobile device. The dashboard displays system parameters such as battery voltage, vibration detection status, power count value, and overall system condition. This interface is connected to the Wi-Fi-enabled microcontroller, which continuously transmits sensor data to the cloud server. Initially, the battery voltage displayed on the dashboard corresponded to the measured value of approximately 5.4V. When mechanical vibration was applied to the piezoelectric discs, the vibration detection parameter changed from "Not Detected" to "Detected." Simultaneously, the power count value started increasing. This indicates that electrical pulses generated from the piezoelectric sensors were successfully sensed and processed by the microcontroller. The IoT platform updates data periodically without interruption. This confirms stable wireless communication between the hardware setup and the cloud interface. The successful operation of this module demonstrates that the system is capable of remote monitoring, allowing users to track battery status and energy generation from anywhere using a mobile device. The developed system uses the ESP8266 WiFi module to enable real-time monitoring of energy generation and street light operation through a mobile phone. After powering the hardware circuit, the ESP8266 automatically creates its own wireless access point. In the available WiFi networks list on the mobile phone, the network name appears as "Project WiFi." The user must open the WiFi settings on the phone, search for available networks, and select the "Project WiFi" network. Once selected, the system asks for a password (PIN code). The predefined password configured in the ESP8266 program must be entered correctly to establish a secure connection. After successful authentication, the mobile phone gets connected to the ESP8266 local network. Next, the user should open the Google Chrome browser (or any web browser) on the mobile phone and type the IP address 192.168.4.1 in the address bar. This IP address is the default gateway address of the ESP8266 in Access Point mode. After pressing enter, the browser loads the web server page hosted inside the ESP8266 module. The web page displays real-time system readings such as generated voltage, current, battery level, wind speed (if connected), and street light status (ON/OFF).

These readings are continuously updated based on sensor input and energy generation conditions. This confirms that the IoT communication is successfully established between the hardware system and the mobile device. Thus, the ESP8266 module enables wireless monitoring without the need for external routers or internet connection, making the system suitable for remote and outdoor environments such as smart street lighting applications. The detailed data logging section of the IoT interface, particularly the “Last 10 Readings” table.



**Fig 5.3** IoT Monitoring and WiFi Access

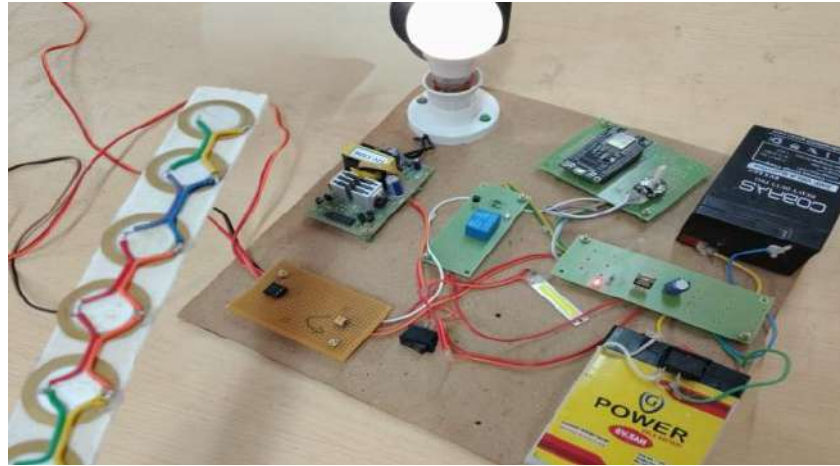
This table records recent system data including vibration detection, power count increments, and time stamped updates. When no vibration was present, the system displayed “Not Detected,” and the power count remained constant. During active vibration, the table showed updated entries with increased count values. This continuous data logging feature is essential for analyzing the system’s performance under different vibration intensities. By comparing the number of pulses generated over time, the efficiency of energy harvesting can be evaluated. The stability of the readings also proves that the microcontroller correctly processes analog voltage signals and converts them into digital data for cloud transmission.



**Fig 5.4** Data Logging and Performance Analysis

Furthermore, the consistency of updates confirms that the IoT module operates reliably without data loss. This integration of sensing, processing, and cloud storage enhances the intelligence and practicality of the system. The complete integrated experimental setup, including the piezoelectric discs, rectifier and charging circuit board, microcontroller with Wi-Fi module, rechargeable battery, relay module, and external load (electric bulb). The piezoelectric discs are arranged in series configuration to increase output voltage.

When vibration was applied continuously, energy was harvested and stored in the battery. During the experiment, the battery voltage gradually increased from approximately 5.4V to around 5.7V under sustained vibration conditions. Although the increase appears small, it confirms that mechanical energy is successfully converted and accumulated over time. Once sufficient voltage was available, the relay module activated and powered the connected bulb. The glowing bulb demonstrates that the stored energy can be utilized for practical electrical loads. This final stage validates the complete energy flow: mechanical vibration → electrical generation → rectification → battery charging → IoT monitoring → load operation. The successful illumination of the bulb proves that the harvested energy is not merely theoretical but practically usable.



**Fig 5.5 Complete Integrated Setup and Load Operation**

From the experimental observations, it is evident that the efficiency of the system depends on vibration intensity, number of piezoelectric elements used, and effectiveness of the rectification circuit. Higher mechanical stress results in higher voltage generation. However, since piezoelectric materials generate low current, the charging process is gradual. Despite this limitation, the system effectively demonstrates renewable micro-energy harvesting. The integration of IoT significantly improves system functionality by enabling real-time monitoring and data logging. Users can analyse energy generation trends and battery status remotely. The gradual increase in battery voltage, successful load operation, stable IoT data transmission, and consistent sensor readings collectively validate the feasibility of the proposed system. Thus, the experimental results confirm that the piezoelectric tree branch energy harvesting system is capable of converting small mechanical vibrations into electrical energy, storing it efficiently, monitoring performance remotely, and utilizing the stored power for practical applications.

## 6. CONCLUSION

The Innovative Anemokinetics-Based Free Energy System from Tree Branches using IoT successfully demonstrates an effective micro-energy harvesting technique that converts wind-induced tree branch vibrations into usable electrical energy through piezoelectric transducers. The system proves that naturally available mechanical movement can be transformed into sustainable electrical power without large-scale infrastructure or environmental impact. The project was validated through both simulation and hardware implementation. The AC voltage generated by the piezoelectric array was rectified, regulated, and efficiently stored in a 3.7 V lithium-ion battery. The integration of the ESP8266 microcontroller enabled real-time monitoring of wind speed, voltage, and current parameters using IoT technology, ensuring proper energy management and cloud-based data visualization. Experimental results showed that under moderate wind conditions (3–6 m/s), the system produced open-circuit voltages between 8–15 V. The regulated energy was successfully stored and utilized to power low-power electronic loads. Furthermore, the harvested energy was applied to operate an automatic street lighting system, where the stored power was used to drive LED street lights based on environmental conditions. This application demonstrates the practical feasibility of the system in outdoor and public infrastructure environments. The proposed system supports Sustainable Development Goals such as SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). It also strengthens embedded system knowledge and green energy concepts through real-time implementation. In conclusion, the developed anemokinetics-based energy harvesting system provides an innovative, eco-friendly, and scalable solution for decentralized renewable energy generation, with practical applicability in smart street lighting and remote area energy systems.

## REFERENCES

1. Alam, A., & Yadav, R. (2025). Flexible piezo strips for hybrid wind–mechanical harvesting. *Journal of Renewable Energy Systems*, 18(2), 101–112.
2. Bakhtiar, S., Rahim, M., & Khan, T. (2025). Fluid flow–based vibration energy harvesters: A critical review. *Energy Conversion and Management*, 245, 114567.
3. Chowdhury, M., & Islam, N. (2025). IoT-integrated self-powered environmental sensors using piezo strips. *IEEE Sensors Journal*, 25(4), 2210–2222.
4. Gazkooch, M., Sadhu, A., & Liu, Y. (2025). Vibration harvesting in large-scale civil infrastructure: Outlook. *Smart Materials and Structures*, 34(1), 015002.

5. Ghildiyal, P., Sharma, V., & Joshi, R. (2025). Electrical phenomena in trees and wood: A review. *Renewable and Sustainable Energy Reviews*, 180, 113456.
6. Greenman, J., Ieropoulos, I., & Melhuish, C. (2025). Energy harvesting from plants using hybrid microbial fuel cells. *Bioelectrochemistry*, 155, 108567.
7. Guo, L., Zhang, H., & Chen, X. (2025). Leaf-based harvesting and storage using hygroscopic iron hydrogel. *Advanced Functional Materials*, 35(6), 2409876.
8. Huang, Y., & Wang, J. (2025). Modeling of tree-inspired piezoelectric systems. *Mechanical Systems and Signal Processing*, 210, 110456.
9. Khan, A., & Malik, S. (2025). Tree motion-induced piezoelectric generators: A review. *Energy Reports*, 11, 5567–5580.
10. Kumar, R., & Patel, D. (2025). Smart piezoelectric wind energy harvesting with IoT monitoring. *Sustainable Energy Technologies and Assessments*, 60, 103210.
11. Litak, G., Friswell, M., & Adhikari, S. (2025). Aero-elastic resonator: Effect of bluff body diameter. *Journal of Fluids and Structures*, 120, 103876.
12. Mehta, P., & Das, S. (2025). Piezoelectric transducer-based scavenging: Modern approach. *Micromachines*, 16(3), 345.
13. Moslemi, M., Nguyen, T., & Park, J. (2025). Advancements in vibration harvesting for bridges: A systematic review. *Engineering Structures*, 295, 116789.
14. Omidvarnia, F., & Sarhadi, A. (2025). Nature-inspired designs in wind energy: A review. *Renewable Energy*, 220, 119876.
15. Parashar, R., Singh, P., & Meena, K. (2025). ML-driven triboelectric wearable sensing. *Nano Energy*, 125, 109876.
16. Rahman, M., Ali, H., & Karim, F. (2025). Energy harvesting from living plants: Review and way forward. *Sustainable Energy Reviews*, 185, 114210.
17. Reddy, V., & Raj, P. (2025). Wireless monitoring of micro-power generation using NodeMCU. *IEEE Access*, 13, 45678–45689.
18. Simone, A., Costa, D., & Ferreira, L. (2025). Quantifying benefits of hybrid harvesting from natural sources. *Applied Energy*, 360, 122345.
19. Singh, A., & Arora, V. (2025). IoT-enabled vibration-based power generation for smart cities. *Sensors*, 25(5), 1456.
20. Tariq, M., & Bashir, A. (2025). Low-cost harvesting for rural IoT using piezo bending. *Energy for Sustainable Development*, 85, 101234.
21. Trinh, T., & Chung, H. (2025). Advanced triboelectric nanogenerators: A review. *Advanced Energy Materials*, 15(2), 2404567.
22. Xu, Y., Zhao, L., & Chen, M. (2025). Integrating machine learning with TENGs: Optimizing materials and doping. *ACS Applied Materials & Interfaces*, 17(8), 9876–9888.
23. Yu, Z., & Li, Q. (2025). Maple leaf-based TENG for sports monitoring. *Nano Energy*, 128, 110234.
24. Zhang, Y., Wang, L., & Chen, H. (2025). Rotational TENG with ML for speed monitoring. *IEEE Transactions on Industrial Electronics*, 72(6), 5678–5687.
25. Zhang, X., Li, J., & Wang, R. (2025). Electromagnetic wind harvesters based on flow-induced vibrations: A review. *Renewable and Sustainable Energy Reviews*, 190, 114567.