Harnessing Wind Energy: Development of a Mini Windmill Power Generation System

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Abstract: This project introduces a new methodology for harvesting wind energy using the design and development of a power generation miniature windmill system. The system uses a horizontally rotating prototype of a windmill equipped with a DC dynamo generator, which serves the possibility of electricity generation through magnetic coupling between the rotating and stationary coils in the presence of wind. A central feature of the setup is the Atmega328 microcontroller, which both powers the system and monitors and displays voltages on an LCD while charging a battery all at the same time. The three LED indicators help it track the real-time record of power being generated. This project is an exemplary sustainable generation of electricity where renewable resources are utilized optimally without reliance on fossil fuels and no harmful pollutants. Therefore, it presents an eco-friendly small-scale energy production solution.

Keywords – Wind Energy, Prototype, Arduino, LEDs, LCDs, Voltage Divider, DC Dynamo Generator

I. INTRODUCTION

An increased demand in renewable energy has necessitated great improvement concerning wind energy technology, with an emphasis on small-scale turbines. These systems are much needed forms of sustainable energy solutions to ensure reliable energy supplies in remote locations where other traditional power sources may not be assured or readily available. According to Forsyth (1997), small-scale wind turbines play a crucial role in increasing energy accessibility and reliability [1]. Of these, the Savonius wind turbine is very simple and efficient in low wind and, therefore, a prime contender for decentralized energy production (Homzah et al., 2021). Hybrid renewable energy systems, incorporating more solar and wind power, have added further efficiency to the generation of energy [2].

Pagola et al. 2019 explores benefits in introducing wind turbines and photovoltaic panels using real-time digital simulation platforms with Arduino technology to maximize the energy production [3]. Hybrid systems help find solutions to the problem of intermittency with renewable sources, maximizing the capture of energy by providing good supplies of power. This is supported by Al Rakib et al. (2022) through demonstration of how an Arduino-based energy storage system can efficiently utilize and manage energy captured from solar and wind towards reliability and integration [4]. Novel designs, such as the Adaptive Hybrid Darrieus Turbine (AHDT) further augmented performance under differing wind conditions. Kumar et al. (2017) discusses the appropriateness of such designs for not only urban application but rural use as well and improves adaptability along with efficiency in small wind turbines [5]. Li et al. (2020) further state that lab-scale models replicating utility-scale systems are of extreme importance to enable a cost-effective means for testing and validation of performance [6]. Cao et al. (2012) summarize trends in turbine generator technologies that reflect, through materials and design advancements, performance and reliability improvements that are significant [7]. From this foundation, the work of Lavassas et al. (2003) takes off to discuss the adequacy of wind turbine towers regarding structural integrity and, hence, places emphasis on a sound engineering basis with regard to providing dependable stability over the long term in changing situations [8].

Continuous development of small wind turbines and hybrid renewable energy systems is essential in addressing the needs of energy globally. For this purpose, these systems will look forward to utilizing the latest developments in design, control strategies, and integration technologies that will provide a sustainable, efficient, and reliable source of energy for various applications. Continued exploration and innovation are critical in seeking to advance renewable adoption and move toward environmental sustainability.

II. METHODOLOGY

The miniature wind energy harvesting system was designed and implemented based on a comprehensive methodology to ensure efficient energy capture, conversion, and monitoring. The design focuses on integrating key components in a compact and efficient manner to simulate a small-scale renewable energy system. Starting with the energy acquisition phase, the mechanical energy generated by the wind turbine is transferred to a generator for conversion into electrical energy. This energy is then processed, measured, and visualized in real time to demonstrate system functionality and performance.

The system's core components are interconnected in a manner that ensures a seamless flow of energy and data. The block diagram (Figure 1) visually represents this interconnectedness, highlighting how the mechanical energy from the wind turbine is converted into electrical energy and subsequently measured using sensors. The data gathered from the sensors is processed by the microcontroller, which serves as the central control unit, enabling real-time visualization of system parameters such as speed, voltage, and current.

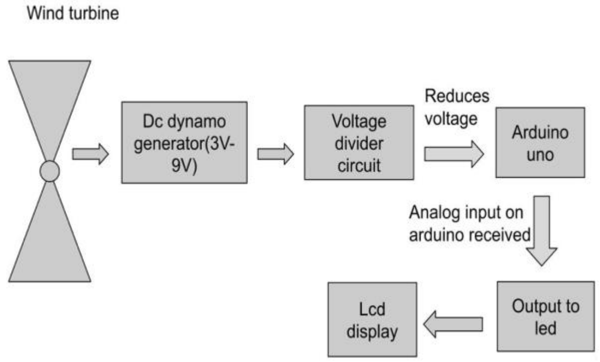

Fig. 1. Block Diagram of circuit

The methodology also incorporates provisions for modularity and adaptability. For example, the system is designed to operate with a small toy fan as the wind turbine, making it easy to simulate varying wind conditions by manually adjusting the fan speed. This allows for a practical demonstration of how changes in wind input affect the system's performance. Additionally, the inclusion of sensors ensures accurate measurement of the electrical parameters, providing reliable data for analysis. These features, combined with a focus on real-time monitoring and visualization, make the methodology robust and effective for small-scale renewable energy applications.

2.1 Circuit Design:

The circuit design for the mini windmill power generation system was developed using Tinkercad, a user-friendly online circuit simulation tool. This virtual platform facilitated the creation and testing of the circuit prior to its physical implementation, allowing for adjustments and optimizations in a simulated environment. The circuit diagram, depicted in Figure 2, illustrates the various components and their interconnections, providing a clear representation of how each element integrates into the overall system.

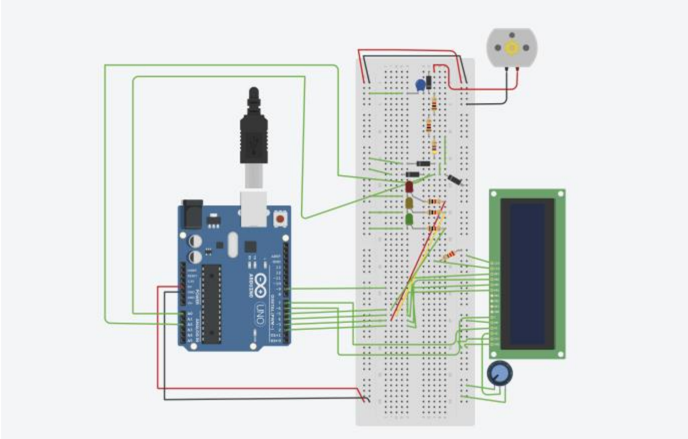

Fig. 2. Tinker cad circuit diagram

2.2 System Overview

The proposed miniature wind energy harvesting system, as illustrated in Figure 1, comprises several key components :

a. Wind Turbine**:** A Savonius-type wind turbine is employed to capture kinetic energy from the wind.
b. DC Dynamo Generator: Converts the mechanical energy from the turbine into electrical energy.
c. Voltage Divider Circuit: Reduces the voltage output from the generator to a suitable level for the Arduino.
d. Arduino Uno: Microcontroller that processes the voltage input, controls the system's operation, and communicates with the display and LEDs.
e. LCD Display: Displays real-time voltage readings and system status.
f. LED Indicators: Provide visual feedback on the system's operational status.

2.3 Software Development

The Arduino Integrated Development Environment (IDE) was utilized to develop the code for the microcontroller. This code was specifically designed to read voltage and current measurements from the DC dynamo generator, display these readings on the LCD, and control LED indicators based on the levels of power generation. Additionally, it monitors the battery charging status and implements a simple control algorithm aimed at optimizing energy output. This comprehensive approach ensures effective management of the system's performance while providing real-time feedback on power generation.

2.3 Testing and Evaluation

The assembled mini windmill power generation system was tested in a controlled environment using a wind tunnel to evaluate its performance under varying conditions. During the testing process, the wind speed was adjusted to assess how it impacted the system's efficiency. Key parameters measured included the voltage output from the DC dynamo generator, the current drawn by the system, the overall power output, and the battery charging rate. The experimental data collected during these tests were thoroughly analyzed to evaluate the system's efficiency and reliability, providing insights into its operational effectiveness and areas for potential improvement.

III. PROPOSED TECHNIQUE

The voltage divider circuit, as shown in Figure 3, is a key element in protecting the components of the miniature windmill power generation system. This circuit is specifically designed to regulate the variable voltage output generated by the DC dynamo, ensuring compatibility with the operational limits of the Atmega328 microcontroller and other sensitive electronics. By employing a combination of resistors, diodes, and a capacitor, the circuit mitigates the risks associated with overvoltage, reverse current, and transient fluctuations.

The primary function of the voltage divider is to scale down the output voltage of the DC dynamo to a level suitable for the microcontroller. Resistors are configured to divide the voltage proportionally, maintaining the input voltage within the safe range. To further enhance protection, a 5.1V Zener diode is included in the design. This diode clamps the voltage, preventing it from exceeding the microcontroller's maximum input limit, thus safeguarding against damage caused by overvoltage conditions, especially under high wind speeds.

In addition to regulating voltage, the circuit incorporates Schottky diodes to prevent reverse current flow. These diodes ensure that the electrical current flows unidirectionally, protecting the generator and other components from potential backflow-induced damage. Furthermore, a 1μF capacitor is integrated into the circuit to smooth out transient fluctuations in the voltage supply. This reduces electrical noise and stabilizes the input voltage, enabling accurate voltage measurements and consistent system performance.

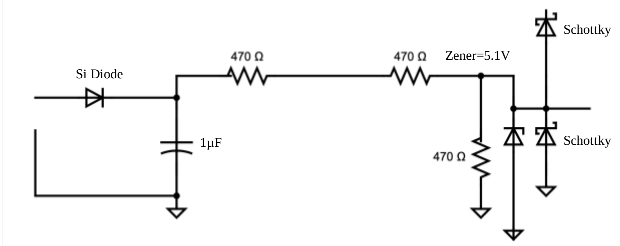

Fig. 3. Voltage divider circuit

The voltage divider circuit plays a pivotal role in conditioning the electrical output of the windmill for safe and reliable use by the system's electronics. Its design not only safeguards the microcontroller and associated components but also contributes to the overall efficiency and durability of the wind energy harvesting setup. By addressing challenges such as voltage variability and electrical noise, the circuit ensures stable operation, enabling real-time monitoring and efficient power generation.

IV. HARDWARE PROTOTYPING

The hardware prototyping process involved designing and assembling the essential components required for the wind energy conversion system. The setup integrates a wind turbine (toy fan), DC dynamo generator, voltage divider circuit, current sensor, and Arduino microcontroller, ensuring seamless energy conversion and real-time monitoring. Each component was interconnected to facilitate energy flow and data acquisition, with the Arduino serving as the central processing unit.

Figure 4 illustrates the complete hardware circuit, highlighting the configuration of components and their interconnections. The diagram emphasizes the energy transfer from the turbine to the generator and onward to the sensors and display module, showcasing how the system achieves its intended functionality in a compact and efficient design.

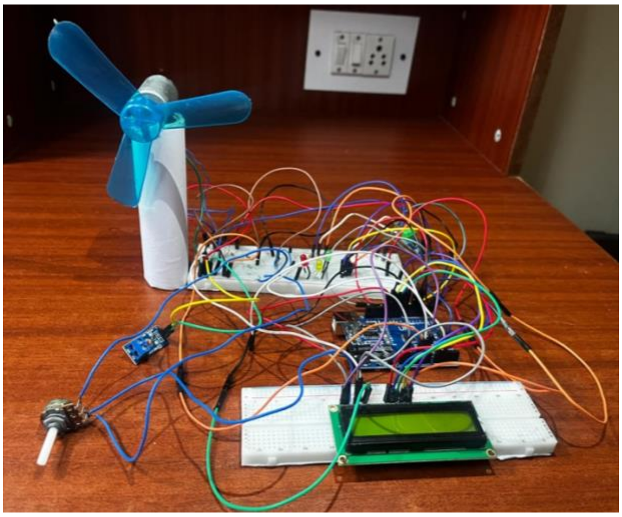

Fig. 4. Windmill prototype circuit

4.1. Wind Turbine

The primary component that captures wind energy is blades. They are typically made of aerodynamically and of lighter materials. Following this we have hub, which connects blades to rotor. Rotor shaft helps in the rotational motion from blades to the dc dynamo generator.

4.2. DC Dynamo generator

The DC Dynamo generator works on the principle of electromagnetic induction. When a conductor cuts through magnetic field lines, an electromotive force (EMF) is induced, which causes current to flow. In a DC dynamo generator, a coil of wire rotates within a magnetic field, generating an alternating current (AC). A commutator and brushes are used to convert this AC into direct current (DC). The generator is selecting based on the power rating and based on its efficiency to minimize lose.

4.3. Voltage Divider

The voltage divider circuit plays a crucial role in the mini windmill power generation project by enabling the safe measurement of voltage output from the DC dynamo generator. Given that the generator can produce a high voltage output, the voltage divider reduces this voltage to a level that is compatible with the Arduino's analog input range. This ensures that the microcontroller can accurately read and process the voltage data without risking damage to its components.

4.4. Voltage Sensor
The voltage sensor (either a built-in analog input pin-on the Arduino or a dedicated voltage sensor) measures the voltage from the voltage divider.

4.5 Current Sensor
They are crucial components as they monitor the electrical current flowing through the system. They handle efficient monitoring of the anomalies in system like short circuit. They also help optimize the charging process to prevent overcharging and undercharging.

4.6. LCDs and LEDs
The Arduino controls the LCD to display the measured voltage and the displayed current and the LEDs to indicate different voltage ranges i.e., first led will light up in a voltage range of 0-1.5v, following the second led will light up in voltage range of 1.5v-3.5v and the third led will light up in a voltage greater 3.5v.

4.7. Resistors and Capacitors
Resistors, Capacitors are used in the circuit in the voltage divider circuit and diode are used for the uni-directional flow of current to the LEDs.

V. SIMULATION AND ALGORITHM

5.1. Simulation Considerations
The simulation considerations for the mini windmill power generation system involved several key steps to ensure effective circuit design and functionality Components were selected based on specific specifications and values, facilitating the simulation of the circuit using Tinkercad. The DC generator output was modeled as a variable voltage source to simulate different wind speeds. A voltage divider circuit was designed using resistors to scale down the generator's voltage to levels compatible with the Arduino's analog input range.
Voltage readings were obtained through the Arduino's built-in Analog-to-Digital Converter (ADC), while current levels were calculated using Ohm's Law based on simulated voltage and resistance values. The LCD display was simulated to show real-time voltage and current values, and LED indicators were triggered based on predefined voltage thresholds derived during circuit analysis. Resistor and capacitor values were optimized for the voltage divider circuit, and diodes were included to regulate current flow to the LEDs. This structured simulation approach enabled comprehensive testing, ensuring the correct functionality of all components within the system prior to physical implementation.

5.2 Algorithmic Implementation
The system algorithm was developed to control and monitor the power generation process efficiently. The key steps of the algorithm are as follows:

1. Initialization:
    - The Arduino initializes serial communication and the LCD display.
    - Pins for LEDs are set as outputs, ensuring readiness for real-time voltage range indication.
2. Sensor Data Acquisition:
    - Voltage is read from the DC generator via the voltage divider circuit connected to an analog input pin.
    - Current is measured using an analog input pin, with values derived from calibration factors.
3. Data Processing:
    - Analog sensor readings are converted into actual voltage and current values using calibration formulas:
      $\text{Voltage} = \text{Raw Reading} \times (\frac{5.0}{1023.0}) \times \text{Scaling Factor}$
      $\text{Curren t} = \text{Raw Reading} \times (\frac{5.0}{1023.0}) \times \text{Scaling Factor}$
    - Voltage values are capped at a maximum threshold (6.0V) to ensure system safety.
4. Power Calculation:
    - Power generated is calculated using the formula:
      Power= Voltage × Current
5. Display and Feedback:
    - Real-time current values are displayed on the LCD, while voltage, current, and power are logged to the serial monitor for analysis.
    - LEDs provide visual feedback based on the voltage range:
    - 0–1.5V: LED A is ON.
    - 1.5–4.5V: LEDs A and B are ON.
    - Above 4.5V: LEDs A, B, and C are ON.
6. Simulation Validation:
    - Voltage and current readings, as well as LED behaviour, were verified against the simulation model to ensure alignment between theoretical and practical results.

This combined approach of simulation and algorithmic implementation ensured seamless integration of hardware and software. The structured methodology provided a robust framework for monitoring and analyzing the performance of the mini windmill power generation system, enabling accurate measurement of voltage, current, and power output while ensuring system reliability.

VI. RESULTS AND ANALYSIS

The operation of the windmill prototype begins when the fan blades start rotating. This motion drives the circuit, which is controlled by an Arduino microcontroller. The LEDs connected to the circuit glow at varying intensities depending on the voltage generated by the turbine, which is influenced by the rotational speed of the blades. Simultaneously, the Arduino monitor displays the real-time values of speed, voltage, and current, while the voltage and current values are also shown on an LCD screen. When the fan blades are stationary, the readings for speed, voltage, and current are all zero, indicating that no electrical output is generated in the absence of rotation. The experimental results demonstrate the relationship between the rotational speed of the turbine, the generated voltage, and the resulting current. By varying the turbine's speed (measured in RPM), corresponding voltage and current values were recorded to evaluate the miniature wind energy harvesting system's performance. These values, summarized in Table 1, highlight the system's ability to generate electrical power under different operating conditions, showcasing how changes in speed directly influence the electrical output.

Speed (RPM)	Voltage (V)	Current (A)
200	1.2	0.05
400	2.3	0.07
600	3.5	0.09
800	4.7	0.11
1000	5.6	0.13
1200	6.2	0.14
1400	7.0	0.15
1600	7.6	0.16
1800	8.2	0.17
2000	8.8	0.18

Table 1 Voltage and Current values obtained at various speed

The graph in Figure 5 illustrates the relationship between the rotational speed of the turbine and the voltage generated. The results exhibit a linear trend, where the voltage increases proportionally with the turbine's speed. Starting from approximately 1V at 200 RPM, the voltage steadily rises to about 9V at 2000 RPM. This behavior is consistent with Faraday's law of electromagnetic induction, which states that an increase in the speed of rotation enhances the rate of change of magnetic flux, thereby inducing a higher electromotive force (EMF).

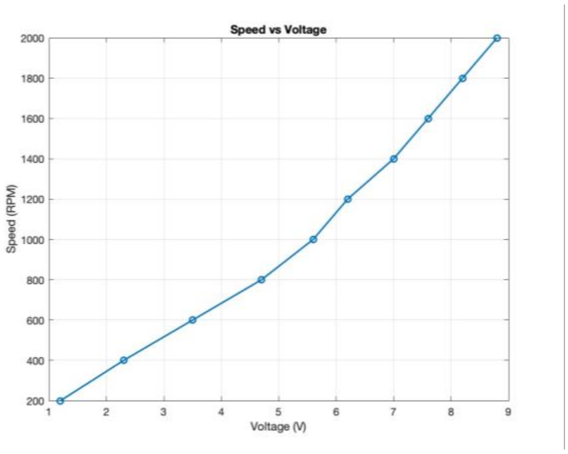

Fig. 5 MATLAB plot of Speed vs Voltage

Fig. 6 shows the graph between turbine speed and current output. Similar to the trend observed in Fig. 1, this plot reveals a linear increase, with the current rising from 0.05A at 200 RPM to 0.18A at 2000 RPM. This behavior confirms that higher turbine speeds result in greater electrical output, demonstrating the system's efficiency in converting mechanical energy into electrical energy.

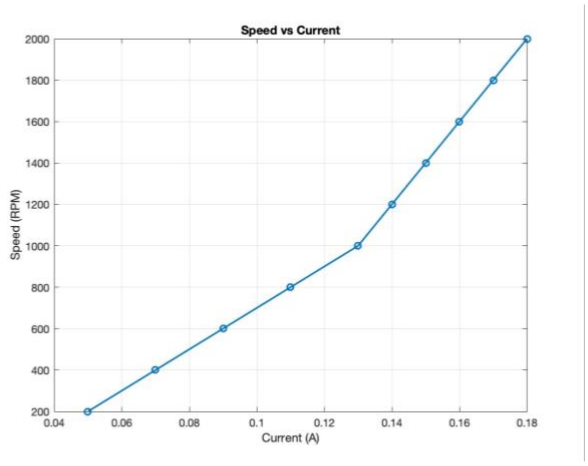

Fig. 6 MATLAB plot of Speed vs Current

Fig. 7 illustrates the graph between voltage and current, showing a linear relationship. The current increases steadily with voltage, ranging from 0.05A at 1.2V to 0.18A at 8.8V. This proportional increase reflects the system's constant load resistance, indicating that the current output is directly dependent on the voltage generated by the wind turbine.

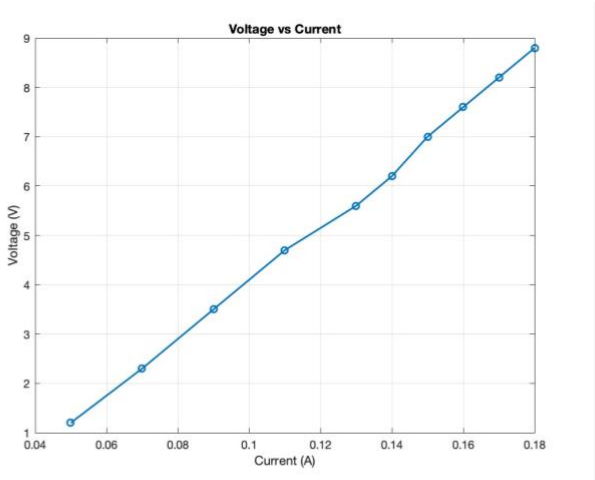

Fig. 7 MATLAB plot of Voltage vs Current

The analysis of these graphs reinforces the experimental findings, highlighting the linear relationships between speed, voltage, and current. These results showcase the predictable performance of the miniature windmill prototype, providing valuable insights into its design, efficiency, and potential for small-scale renewable energy applications**.**

VII. CONCLUSION

The windmill prototype developed in this project successfully demonstrates the ability to harness wind energy and convert it into usable electrical energy, showcasing the potential of renewable resources in sustainable power generation. By effectively integrating mechanical and electrical components, the system captures kinetic energy from the wind, generates electricity through a DC dynamo generator, and monitors its performance in real-time. The project adeptly combines a wind turbine with a voltage divider circuit, allowing for accurate measurement and display of voltage readings on an LCD screen. Additionally, the incorporation of a current sensor powered by an Arduino microcontroller enables the generation and real-time display of both voltage and current values, providing immediate feedback on power generation levels through visual indicators.
This prototype not only highlights the viability of small-scale wind energy systems but also underscores the importance of data-driven monitoring for optimizing performance. The inclusion of visual indicators for power generation fosters a deeper understanding of the system's functionality and efficiency. Looking ahead, advancements in turbine design, material selection, and control strategies could significantly improve energy capture and conversion rates, making the system more robust and sustainable. By addressing these aspects, the prototype has the potential to serve as a scalable and efficient solution for renewable energy generation in diverse applications, contributing meaningfully to the global transition toward clean energy sources.

APPENDIX

```
#include <Wire.h>
#include <LiquidCrystal.h>
// Define pins
const int rs = 12; // Register Select
const int en = 11; // Enable
const int d4 = 7; // Data pin 4
const int d5 = 8; // Data pin 5
const int d6 = 9; // Data pin 6
const int d7 = 10; // Data pin 7

LiquidCrystal lcd(rs, en, d4, d5, d6, d7);
int ledAPin = 3;
int ledBPin = 4;
int ledCPin = 5;
int voltPin = A0; // Analog input pin for voltage sensor
int currentPin = A2; // Analog input pin for current sensor

// Define variables
double convertedVoltVal = 0.00;
double convertedCurrentVal = 0.00;
double powerGenerated = 0.00;

void setup() {
  Serial.begin(9600);
  lcd.begin(16, 2);

  pinMode(ledAPin, OUTPUT);
  pinMode(ledBPin, OUTPUT);
  pinMode(ledCPin, OUTPUT);
}
void loop() {
  // Read voltage from sensor

  int voltVal = analogRead(voltPin);

 // Read current from sensor (adjust calibration factor as
needed)
  int currentVal = analogRead(currentPin);

 // Filter the readings to reduce noise (optional, adjust filter
coefficients as needed)
  //static int voltFilter = 0;
  //static int currentFilter = 0;
  //voltFilter = (voltFilter * 7 + voltVal) / 8;
  //currentFilter = (currentFilter * 7 + currentVal) / 8;

// Convert raw readings to actual values (adjust calibration
factors as needed)
  convertedVoltVal = (voltVal)*(5.0/1023.0)*0.235;
  if (convertedVoltVal > 6.0) {
    convertedVoltVal = 6.0;
  }
  convertedCurrentVal =(currentVal)*(5.0/1023.0)*0.235 ;
  // Calculate power generated

powerGenerated=convertedVoltVal*convertedCurrentVal
;

  // Display values on LCD

  lcd.setCursor(0, 0);
 // lcd.print("Voltage: ");
  //lcd.print(convertedVoltVal);
  //lcd.print(" V  ");
  lcd.print("Current: ");
  lcd.print(convertedCurrentVal);
  lcd.print(" A");
  //lcd.setCursor(0, 1);
  //lcd.print("Power Gen: ");
  //lcd.print(powerGenerated);
  //lcd.print(" W");
  Serial.print("Voltage: ");
  Serial.print(convertedVoltVal);
  Serial.print(" V, Current: ");
  Serial.print(convertedCurrentVal);
  Serial.print(" A, Power: ");
Serial.println(powerGenerated);
  delay(100);

  // Control LEDs based on voltage (adjust thresholds as
needed)

if (convertedVoltVal >= 0 && convertedVoltVal < 1.5) {
    digitalWrite(ledAPin, HIGH);
    digitalWrite(ledBPin, LOW);
    digitalWrite(ledCPin, LOW);
  } else if (convertedVoltVal > 1.5 && convertedVoltVal <
4.5)
{
    digitalWrite(ledAPin, HIGH);
```

```
    digitalWrite(ledBPin, HIGH);
    digitalWrite(ledCPin, LOW);
  } else if (convertedVoltVal > 4.5) {
    digitalWrite(ledAPin, HIGH);
    digitalWrite(ledBPin, HIGH);
    digitalWrite(ledCPin, HIGH);
  }
}
```

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