Power Frequency Magnetic Field Sensor

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***Abstract*—This project focuses on developing a sensor aimed at remotely detecting power-frequency magnetic fields, particularly those emanating from sources such as high-tension lines and substations, posing potential hazards to humans. The objective is to design a sensor capable of accurately measuring magnetic field levels. Utilizing a linear Hall effect sensor, the project converts magnetic field intensity into voltage output, which is subsequently processed by an Arduino microcontroller to quantify the field strength in Gauss units. The sensor's range spans from 0 to 700 Gauss, accommodating positive and negative magnetic fields. Results are displayed on an LCD screen, providing real-time feedback on magnetic field levels, thus contributing to improved safety measures in environments where exposure to such fields is a concern.**

Keywords—sensor, power-frequency, magnetic, strength

I. Introduction

The objective of this project is to design a sensor to detect the magnetic field level and measure the strength of that magnetic field. At the beginning of the project, as an initial approach, research was done to find some commercially available sensors and different principles that fulfill this objective. In light of this research, it was found that magnetometers and magnetoresistance sensors are prominent in the market. Some used principles were magnetostriction property, electromagnetic induction, and optical properties. Out of these methods, we decided to use a modern technology method as the use of microcontrollers for the sensor. (Dilip Raja, 2015)

The main aim of this project is to generate an electrical signal from a physical variable. All electrical and electronic engineers are capable of doing that. In this project, the physical variable is the magnetic field and the electrical signal is a voltage signal. For this conversion, the SS49E hall effect sensor is used. It generates an analog voltage output in the presence of a magnetic field. This output is highly varying. To filter those variations, capacitors are used. Then, an Arduino microcontroller is used to store the output signal and display it on an LCD. The initial version of this sensor is capable of measuring values in the range of -650 to +650 Gauss.

The application of this project is to make a device that measures the magnetic field strength of Power frequency magnetic fields. It is believed that these PFMFs are hazardous to human health. Some countries have already implemented guidelines for PFMF exposure. (Maalej, 2011) So, this sensor will measure the strength of PFMFs and give a warning when the value exceeds the human exposure limits for PFMFs.

II. Initial Specifications

A. Measurement Quality

This sensor provides a voltage output of 2.7mV for 1 Gauss of magnetic field, indicating the sensitivity is 2.7mV/G. This value is good for the PFMF measurements since they are very sensitive. Other than that, this sensor can measure both positive and negative(opposite direction) magnetic fields stating that it is bipolar. So, if the direction of the magnetic field is changed, the reading will be minus on the display.

B. Range

The sensor design has a range of -650 to 650 Gauss which corresponds to an output voltage range of 0.86 to 4.21 V. This means, the sensor will output a voltage of 4.21 V in the presence of a 650 Gauss magnetic field and 0.86 V to a magnetic field of -650 Gauss. Also, there will be an output voltage of 2.5 V for 0 Gauss condition.

C. Resolution

The resolution of the design is 0.01 Gauss. This value can be improved in future designs by using an amplifier circuit which is used to obtain a voltage gain as well as by using another SS49E and considering the average.

D. Other Specifications

- Operating Temperature: - 40 ^{0}C to 150 ^{0}C
- Operating Voltage: 4.5 V to 6 V
- Offset Error: 0.55 Gauss
- Length of SS49E: 12 mm
- Dimensions of the compartment: 7 cm × 15 cm
- 16 × 2 LCD with I2C module

III. Method

As mentioned in the introduction, the method used in developing the sensor was a combination of an Arduino microcontroller and a Hall effect sensor.

A. *Circuit Diagrams*

Before implementing the circuit physically, we simulated the circuit on *Proteus 8 software* to check whether the magnetic field can be measured using Arduino controllers.

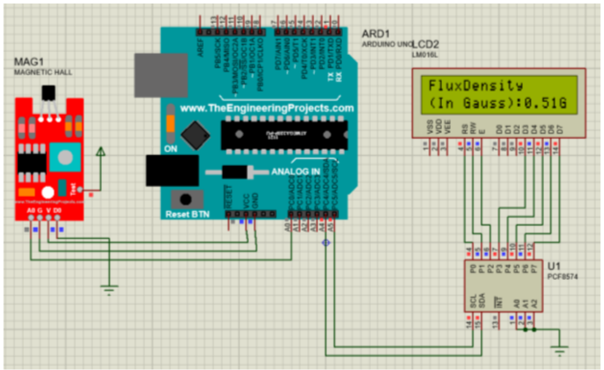

Figure 1: Proteus simulation setup.

Figure 1 consists of components, a linear hall effect sensor module, an Arduino Uno, an I/O expander, and an LCD module. An imaginary magnetic field input is given to the sensor module and the value is observed on the LCD. This helped us a lot to plan implementing the circuit design physically.

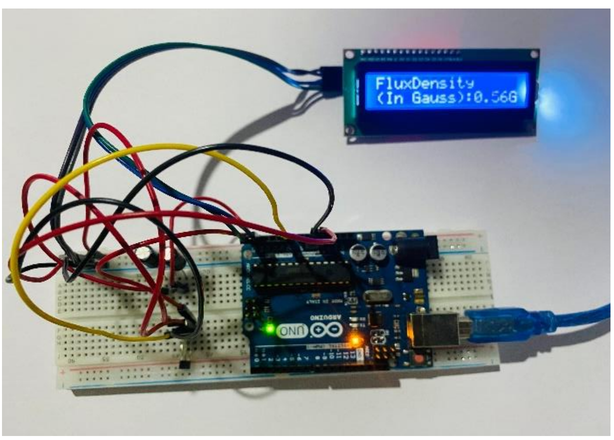

Figure 2: Circuit Setup for the Sensor Design

Figure 2 depicts the physical circuit setup that is used for the magnetic field sensor. It has an SS49E linear hall sensor, two capacitors, an Arduino Uno, and a 16 × 2 LCD.

B. *Principle of Operation*

When a magnetic field comes in contact with the SS49E, it generates a voltage. The maximum voltage output would be 4.21 V which is for a magnetic field of 650 Gauss. As shown in *Figure 3*, there are three pins in the SS49E. Pin 1 is for V_{cc}, pin 2 is for GND, and pin 3 is for V_{out}. The branded surface of the SS49E shows a positive output for the South pole and a negative output for the North pole. (Hareendran, 2019) For the operation of the SS49E, a V_{cc} should be applied. ("SS49E datasheet," 2022) There can be several noises interfering with the output

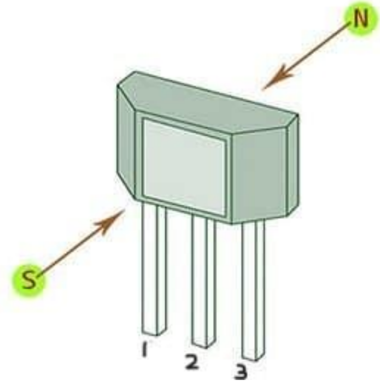

Figure 3: Active region of the SS49E. (Source: Hareendran, 2019)

voltage signal due to the presence of so many wires in the circuit setup. To avoid those interferences, two capacitors are used. Then, the filtered output voltage is directed to the Arduino Uno, and it computes this voltage output and displays it on the LCD as a value in Gauss using the sensitivity of the sensor. The code

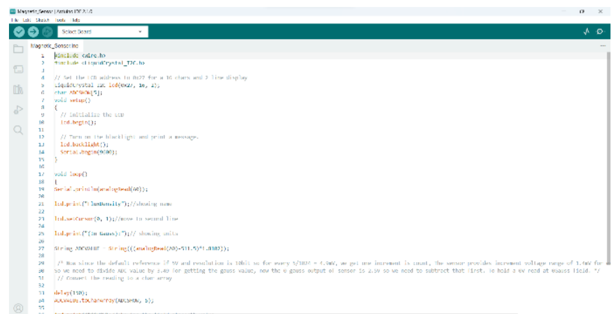

Figure 4: Arduino Code

used for this computation inside the Arduino is shown in *Figure 4*. Inside Arduino, 5 V is represented using 10 bits. Therefore, there are 1023 storing locations to store 5 V. By using this concept, the magnetic field value for one location out of 1023 can be calculated using the sensitivity of the sensor.

Sensitivity of the sensor = 2.7 mV/G

The voltage value of 1 storing location inside Arduino = $\frac{5}{1023}$ V

Gauss value of 1 storing location inside Arduino = $\frac{5}{1023} \times \frac{1000}{2.7}$ G

Output displayed on the LCD = (Analog out) × 1.81 G

C. *Statistical Analysis*

Inside this sensor module, there is only one Hall effect sensor. Averages and standard deviations are calculated according to the readings in *Table 1*.

σ − Standard deviation
x_i − Voltage reading
$\bar{x}$ − Average
n − No. of readings

$$\text{Average } (\bar{x}) = \frac{\text{Sum of Readings}}{\text{No. of Readings}}$$

$$\text{Standard deviation } (\sigma) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n}}$$

Table 1: Averages and Standard deviations of the Output Voltages

Input Magnetic Field (Gauss)	**Average Output Voltage (V)**	**Standard deviation (V)**
-520.0	1.141	0.079
-280.4	1.785	0.077
-100.1	2.231	0.003
-33.7	2.434	0.040
0.0	2.506	0.021
33.7	2.615	0.056
100.1	2.826	0.082
280.4	3.309	0.085
520.0	3.915	0.016

Table 1 shows the average output voltage and its deviation from the average value considering the given input magnetic field for the sensor using the readings obtained from *Table 2*. These values are calculated using the two equations given above.

D. *The Sensor Module*

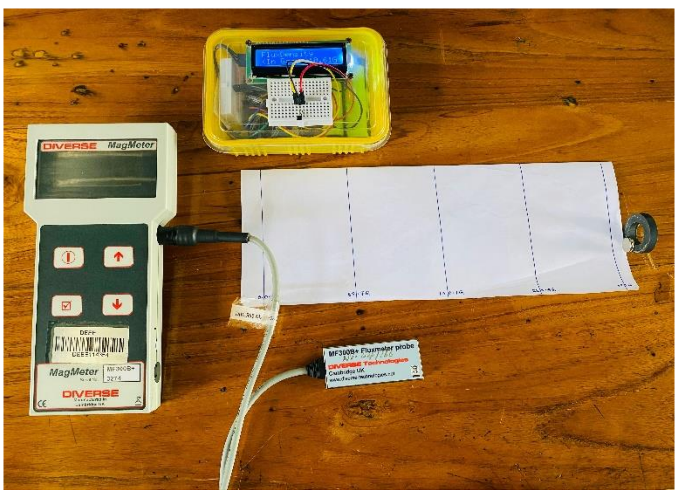

Figure 5: Calibration Setup

Figure 5 shows the calibration setup that was used for calibrating our sensor. We used a magnetic fluxmeter and a permanent magnet for this setup. The permanent magnet was placed at a fixed position and the strength of the magnetic field was measured at different positions on a white paper using the fluxmeter up to a resolution of 0.1 Gauss. Then, the measured values were marked on those positions to obtain known input magnetic fields for the sensor. Once the setup was done, we kept the sensor at those marked positions and measured the output voltage produced by the sensor using Arduino. By changing the side of the permanent magnet, negative magnetic field values were also obtained. For the calibration to be complete, we took 5 sets of such readings at five different times as shown in *Table 2*.

The sensor module is powered by a 5 V DC battery and the SS49E, the sensing element is isolated from the battery, and wires using the yellow-colored compartment as shown in *Figure 5*. This isolation is done to avoid interferences and variations in the displayed output.

IV. RESULTS

A. *Observations*

Table 2: Variation Output Voltage with Input Magnetic Field

Input (Gauss)	**Output Voltage Variation (V)**				
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**
-520.0	1.123	1.296	1.088	1.113	1.085
-280.4	1.743	1.750	1.939	1.742	1.748
-100.1	2.235	2.229	2.225	2.231	2.232
-33.7	2.410	2.421	2.425	2.511	2.399
0.0	2.486	2.523	2.532	2.476	2.510
33.7	2.602	2.582	2.591	2.572	2.724
100.1	2.825	2.753	2.773	2.982	2.795
280.4	3.245	3.257	3.321	3.249	3.469
520.0	3.912	3.904	3.945	3.901	3.913

Table 2 shows five sets of readings that we took from the calibration setup, *Figure 5*. These readings were used to draw the calibration curve (input-output characteristic) and calculate the sensitivity of the sensor module.

B. *Input-output characteristic curve*

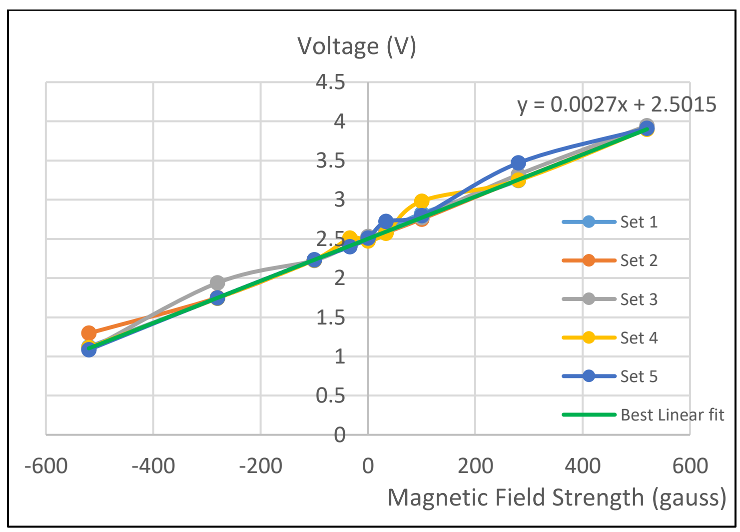

Figure 6: Variation of Output Voltage with Input Magnetic Field

Figure 6 depicts the curves drawn from the data in *Table 2* and the best linear fit curve drawn from the 5 curves is shown using the green color. The characteristics of this best linear fit curve can be used to analyze the results of the calibration process further.

$$y = 0.0027x + 2.5015$$

Therefore, the gradient of the best linear fit curve is 2.7 mV/G, and the intercept is 2.5015 V. The gradient acts as the sensitivity of the sensor and intercept acts as an offset error to the sensor. We know that 2.5 V corresponds to the 0 Gauss state. Thus, the offset error would be 1.5 mV in positive direction.

$$\text{Sensitivity} = 2.7\ \text{mV/Gauss}$$

$$Offset\ Error\ in\ Gauss = \frac{1.5}{2.7}\ G$$
$$= 0.55\ Gauss$$

This value of 0.55 Gauss was always appearing on the LCD at every location even though a magnetic field was not applied.

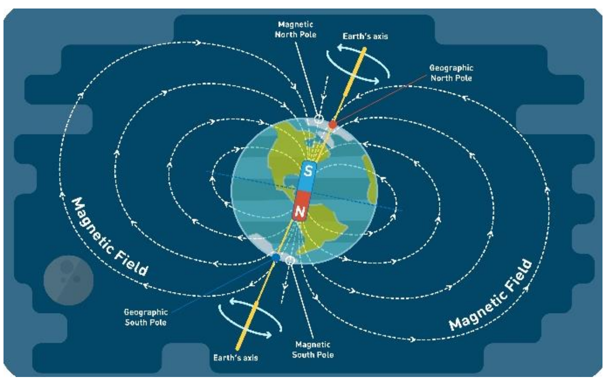

Figure 7: Earth's Magnetic Field Lines (Source: Dobrijevic, 2022: online)

Figure 7 shows the distribution of magnetic field lines due to the presence of a magnet inside Earth's core. They are parallel to the earth and on the surface of the earth, it is like a constant. According to research, the value is found to be in the range of 0.22 Gauss to 0.67 Gauss. (British Geological Survey, n.d.) Hence, it is notable that the offset error also lies in this range. Therefore, a conclusion can be made that this offset error is the Earth's magnetic field.

V. DISCUSSION

A. Difficulties

1) Method Selection: Several methods were proposed for developing the sensor. However, it was required to select only one method. It was a bit of a challenge to select the most suitable method. For that, several factors like cost, easiness of implementation, and simplicity of the setup were considered. By comparing these factors, we decided to follow the method of Arduino microcontrollers.

2) Lower resolution of the sensor to measure PFMF: the magnetic field strength on the Earth's surface caused by the current flow in high tension lines can be calculated using the equation,

$$B = \frac{\mu I}{2\pi r}$$

B – magnetic field strength
μ – permeability of the medium
I – current flow in the conductor
r – distance from the conductor to the point under consideration. (Charles A. Bishop, 2011)

Consider that a current of 100 A flows through the high-tension line. Then, the magnetic field strength below 8 m would be 0.0257 Gauss. However, the resolution of the sensor is 0.01 Gauss. So, 0.0057 part can not be detected from this sensor module. For that, the option was to decrease the range of measurement and improve the sensitivity by using an amplifier circuit to amplify the voltage so that the resolution can be improved. Also, it is possible to implement two SS49Es into the circuit so that the average of two values can be taken to improve the resolution.

3) Earth's magnetic field is much higher than the value due to PFMFs: Earth's magnetic field is in the range of 220 mG to 670 mG. But PFMFs are in the range of 0 to 100 mG. Therefore, this value is slightly smaller. Always, the Earth's magnetic field is parallel to the Earth's surface and the sensor only detects magnetic fields coming perpendicular to it, *Figure 3*. So, by keeping the sensor module parallel to the Earth, the effect of the Earth's magnetic field can be avoided.

4) Interference and Noise: Magnetic fields can be influenced by various external factors, including nearby electronic devices, power sources, and other magnetic materials. Filtering out unwanted noise and minimizing interference from these sources is crucial for obtaining reliable and accurate measurements. So, it is possible to shield the sensor from external electromagnetic interference using magnetic field shielding materials like steel. Also, several filtering techniques, such as analog or digital filters, to suppress noise and unwanted signals can be implemented.

5) Power Consumption: A lot of power is required for the operation of microcontrollers. Also, it is not reliable to change batteries every time. So, advanced semiconductor technologies, such as low-power microcontrollers, and integrated sensor solutions can be utilized to reduce overall power consumption. Furthermore, a thought can be made to run the sensor using solar power which can be done in future developments.

6) Sensor to be used in several environmental conditions: Magnetic field sensors may be deployed in diverse environmental conditions, including outdoor or harsh industrial environments. Ensuring robustness and reliability under varying temperatures, humidity levels, and exposure to dust or moisture requires adequate protection and packaging of the sensor components. For that, the sensor components can be sealed with protective coatings. Also, it is important to conduct extensive environmental testing to validate sensor performance under various conditions, including temperature, humidity, and mechanical stress.

B. Strengths

1) High sensitivity: Hall effect sensors are known for their high sensitivity to magnetic fields, enabling accurate detection of even subtle changes in field intensity. This high sensitivity allows for precise measurement of magnetic fields across a wide range of intensities.

2) Linear response: Hall effect sensors typically provide a linear response to changes in magnetic field strength, making it easier to calibrate and interpret the sensor's output. This linearity simplifies the conversion of voltage readings into meaningful units, such as Gauss, facilitating accurate measurement.

3) Real-time processing: By interfacing the Hall effect sensor with an Arduino microcontroller, real-time processing and analysis of magnetic field data become feasible. The Arduino can quickly convert analog voltage signals from the sensor into digital data, enabling rapid processing and display of magnetic field measurements.

4) Integration with display interfaces: Arduino microcontrollers can easily interface with various display interfaces, such as LCD screens or LEDs, to provide real-time visualization of magnetic field measurements. This capability enhances the usability and accessibility of the sensor system, enabling users to monitor magnetic field levels conveniently.

5) Low Cost: Hall effect sensors and Arduino microcontrollers are relatively inexpensive components, making the overall sensor system cost-effective, especially for educational or research purposes.

C. Weaknesses

1) Limited Resolution: Hall effect sensors have limited resolution, particularly in low magnetic field intensity ranges. This limitation can result in reduced accuracy when detecting small changes in magnetic field strength, especially in applications requiring high precision.

2) Temperature Sensitivity: Hall effect sensors are slightly sensitive to temperature variations, leading to fluctuations in their output readings. Without proper temperature compensation techniques, this sensitivity can introduce errors in magnetic field measurements, particularly in environments with wide temperature fluctuations.

3) Interference and noise: Hall effect sensors and Arduino microcontrollers are susceptible to electromagnetic interference (EMI) and electrical noise from nearby sources, such as motors, power sources, or electronic devices. Without adequate shielding or noise mitigation measures, these external disturbances can degrade the accuracy and reliability of magnetic field measurements.

D. Comparison

The module developed using a Hall sensor with an Arduino microcontroller offers a cost-effective and portable solution for measuring power frequency magnetic fields. While not matching the precision of high-end magnetometers like fluxgate or SQUID magnetometers, it provides sufficient sensitivity and accuracy for many applications. Its compact size, ease of integration, and real-time monitoring capabilities make it ideal for handheld or embedded use, while its affordability and user-friendly interface make it accessible to a wide range of users. Although it may have slightly lower sampling rates and robustness compared to some magnetometers, proper calibration, and shielding can mitigate environmental influences, making it a practical choice for educational projects, field monitoring, and basic research endeavors.

VI. CONCLUSION

In conclusion, the development of our remote power-frequency magnetic field sensor marks a significant advancement in environmental monitoring and human safety. Integrating a linear Hall effect sensor with an Arduino microcontroller has enabled precise detection and measurement of magnetic field levels. Calibration revealed an offset error attributed to the Earth's magnetic field, underscoring the importance of continuous testing procedures in sensor development. Additionally, the sensor's bipolarity allows for measuring both positive and negative magnetic fields, enhancing its versatility in real-world applications.

The significance of this sensor extends to its potential impact on human health and environmental protection. By providing early warnings when magnetic field strengths exceed safe limits, especially near power stations and grid stations, the sensor serves as a proactive safeguard against potential health risks. Furthermore, its isolation using proper magnetic field shields ensures accurate measurements and minimizes interference from external sources, enhancing its reliability in practical settings.

Looking forward, the sensor's adaptability opens doors to diverse applications, from integrating user alerts via SMS or GUI interfaces to automated systems for controlling equipment based on magnetic field measurements. Its suitability for industries, laboratories, homes, and agricultural settings emphasizes its role in resource conservation and human well-being. In essence, the development of this sensor reflects our commitment to innovation and societal progress, paving the way for a safer and more sustainable future.

VII. ACKNOWLEDGEMENT

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