Mechanical Engineering – Scientific Journal, Vol. 42, No. 1, pp. 27–32 (2024)
Number of article: 676
Received: May 16, 2024
Accepted: May 23, 2024
In print: ISSN 1857–5293
On line: ISSN 1857–9191
UDC: 621.317.7:681.586.72]:519.724
https://doi.org/10.55302/MESJ24421027sh

Original scientific paper

DEVELOPMENT OF CURRENT MEASURING INSTRUMENT USING HALL EFFECT

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A b s t r a c t: Isolated current sensing is fundamental in several contexts, including power electronics, automotive, and smart buildings. To meet the requirements of modern applications, current sensors should feature ever larger bandwidth and dynamic range, as well as reduced power consumption and dimension. There are different ways for current measurement like using current transformers or using the Rogowski coils which are not precise enough in many applications and not suitable for use in power electronic measurement systems. For that reason, the Hall effect-based sensor can be used as a very precise alternative with minimum external components. Many modern electronic devices utilize linear Hall sensors to measure current and the magnetic field, as well as to perform switching and latching operations. Within this paper a focus is on the analysis and creation of a current measuring device using the Hall effect sensor SS495A. The mathematical model of the device is calculated experimentally, which then is connected to a microcontroller. The device is connected to the internet and using an IoT platform, an app is created which allows for real time monitoring through the web or a smartphone.

Key words: current sensing; Hall effect; Arduino microcontroller

РАЗВОЈ НА ИНСТРУМЕНТ ЗА МЕРЕЊЕ ЈАЧИНА НА СТРУЈА КОРИСТЕЈЌИ ХАЛОВ ЕФЕКТ

А п с т р а к т: Мерењето на струја е од фундаментално значење во неколку контексти, вклучувајќи ја енергетската електроника, автомобилската индустрија и паметните згради. Со цел да се задоволат барањата на современите апликации, тековните сензори треба да имаат динамичен и зголемен опсег, како и намалена потрошувачка на енергија и димензии. Постојат различни начини за мерење на струјата, на пример користење струјни трансформатори или користење намотки, кои не се доволно прецизни во многу апликации и не се погодни за употреба во електронски мерни системи за напојување. Од таа причина, сензорот заснован на Халов ефект може да се користи како многу прецизна алтернатива со минимални надворешни компоненти. Многу современи електронски уреди користат линеарни Халови сензори за мерење на струјата и магнетното поле, како и за извршување операции на прекинувачи. Во рамките на овој труд фокусот е ставен на анализа и создавање уред за мерење струја со помош на сензорот со Халов ефект SS495A. Експериментално се пресметува математички модел на уред кој потоа се поврзува со микроконтролер. Уредот е поврзан на интернет и со користење на платформата IoT се креира апликација која овозможува следење на податоците во реално време преку веб или преку паметен телефон.

Клучни зборови: мерење на струја; Халов ефект; Ардуинов микроконтролер

1. INTRODUCTION

Current sensing circuits are needed for measurement, monitoring and control of various applications. These circuits are used largely in automotive and power electronics which require current sensing to estimate electrical power and energy. This demand is driven by the recent trends and policies towards smart energy efficient cities, creation, conversion and storage of energy as well as in smart electric vehicles [1–4]. Another relevant use for current sensing is in power modules, in the currentmode loop control of DC-DC converters [5, 6], protection from over current and current leakage.

In several of these applications, the current sensor should satisfy many requirements including low insertion loss, high dynamic range, robustness, high speed, low cost, and reduced physical dimensions. Therefore, it is essential to develop miniaturized and high-performance sensing devices to be possibly embedded within the power system. In this context one of the more widely used techniques for current sensing is the use of the Hall effect. These sensors are sensitive to the magnetic field generated by the current to be detected. Using this effect the current flow which is monitored in the power circuit is kept electrically isolated from the sensor [7]. This isolation of the Hall effect sensors ensures that it is not affected by conducted interference generated by the power system which is monitored which ensures effective use in electromagnetically polluted environment. Sasti et al. [8] have used the Hall effect to develop a high current DC sensor with the ability to measure at 128 amps, while in [9] an educational laboratory was set up using national instruments LabView and an acquisition card and the use of a closed loop Hall effect sensor.

Most magnetic sensors available commercially are so-called Hall devices, which are based on the Hall effect. The Hall effect is the appearance of an electric potential difference in a probe or semiconductor, when there is a magnetic field nearby, perpendicular to the plane of the probe. The original experiment consisted of a metal sheet attached to a glass substrate through which an electric current was conducted (Figure 1). By connecting a galvanometer to the ends of the sheet, at equipotential points, and placing the sheet between the poles of an electromagnet, it was seen that at certain positions of the basic electromotive force and the magnetic field, a suppression of the electric current appeared towards one end of the sheet.

With further tests, it was confirmed that the newly created electromotive force is directly proportional to the product of the magnetic field strength *B* and the current speed *v*.

$$E_H \sim [v \times B] \quad (1)$$

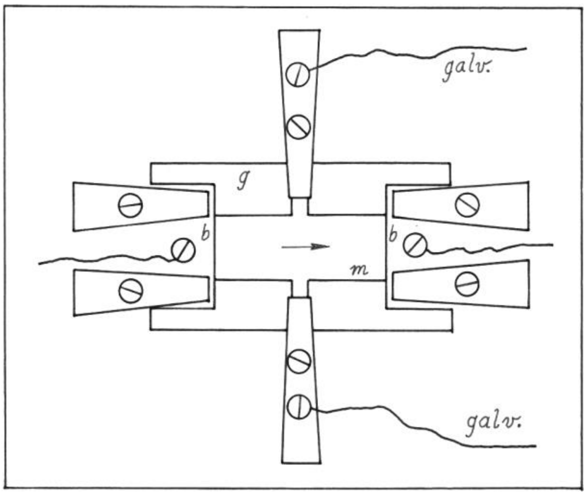

Fig. 1. A sketch of Hall's original experimental arrangement [10]

2. DEVELOPMENT OF CURRENT MEASURING DEVICE

The aim of this work is the development of a device that can measure current flow and send data to a database which can be accessed from anywhere. The use case of the device is mainly focused in household appliances since they are the main power consumers in any home. By connecting to a cloud service, where data processing and collection of real time power consumption data will take place, an application can be created where a statistical overview can be seen of where and how much power is consumed on a daily/monthly basis. In addition, the device for measuring the flow of electric current can serve as a security measure in homes, by sending a predefined notification to the user (example: a certain device has been switched on longer than the specified time, the occurrence of higher consumption than usual when using a certain device, a reminder to turn off the device, a warning about current exceeding the specified limit, etc.). The need of such a device arises since on the market most of the available devices only give information on whether the appliance is turned on or off and they usually come prebuilt into the appliance.

The functional block diagram for this device can be seen on Figure 2.

Fig. 2. Development of current measuring device with cloud connection

2.1. *Measuring and amplification of magnetic field*

In order to approach the realization of the idea of creating a device for measuring the flow and strength of electric current, we firstly need to select an element, i.e., a sensor, from which we will receive data that is directly dependent on the strength of the electric current. Since a magnetic field is created around every conductor through which electric current flows, a suitable solution would be to choose a magnetic sensor. For this purpose the analog Hall sensor Honeywell SS495A is selected, which is a magnetic sensor and at the output it generates a voltage that is directly connected and depends strictly on the strength of the electric current. The SS495A sensor is suitable for its small size, low power consumption, built-in resistors for greater accuracy and temperature compensation, stable output signal and the ability to respond to positive and negative magnetic fields.

The next step in the process is the amplification of the magnetic field in order to obtain a larger range of values that the sensor can detect, which would also increase the accuracy of the output signal. We perform the amplification with a metal part in the shape of a toroid (Figure 3), on which, for additional amplification, we coil up the wire of the conductor where we want to measure the current flow.

Fig. 3. Hall sensor inside a toroid for amplification of magnetic field

A notch in the toroid is made, with the dimensions of the sensor. By inserting the sensor into the notch of the toroid, its position is fixed. The stable position of the sensor is an important factor for obtaining accurate and precise data, because even the slightest change in position can result in a completely different mathematical model.

2.2. *Mathematical model*

Modeling a system means establishing a mathematical model for the behavior of the constituent components of the system itself. Mathematical models represent a set of mathematical relations. They can be obtained analytically or experimentally, i.e., identification of a system. Due to the insufficient amount of available information about the toroid material, we cannot determine the mathematical model for the device analytically. The system for which a mathematical model is developed is shown on Figure 4. The magnetic field which is created when current flows through the conductor is given by the following equation.

$$B = \frac{\mu_0 \mu_r I}{2\pi r}, \quad (2)$$

where B is the magnetic flux density, μ_0, μ_r are the vacuum and relative permeability, respectively, and I is the current. The magnetic flux is measured by the Hall sensor but this value is very low hence it is required to be amplified by a material with high permeability, which is the toroid where the sensor is placed. Since there is a notch in the toroid where the sensor is placed the magnetic flux has a different value which considers the air gap between the sensor and the field concentrator, denoted in the equation as d. This relationship is given by equation 3.

$$B = \frac{\mu_0 \mu_r I}{2\pi(r-d)+d\mu r}. \quad (3)$$

Equation 3 can be rewritten in the same order as equation 2 if an effective permeability is considered.

$$B = \frac{\mu_0 \mu_e I}{2\pi r}, \quad (4)$$

where the effective permeability can be calculated as:

$$\mu_e = \frac{\mu_r}{1+\frac{\mu_r d}{2\pi r}-\frac{d}{r}}. \quad (5)$$

The Hall sensor outputs a voltage whose relation can be described with the following equation, (eq. 6). Further explanation and a deep dive in current measurement in power electronic can be found in [11].

$$V_{\text{out}} = \left(\frac{s\mu_0\mu_e}{2\pi r}\right) I + V_{\text{offset}} \qquad (6)$$

The value of the offset is directly affected by the input voltage of the sensor, where $V_{\text{offset}} = \frac{V_{\text{cc}}}{2}$. The value of the constant that directly connects the current in the conductor and the output voltage from the sensor $\left(\frac{s\mu_0\mu_e}{2\pi r}\right)$ needs to be experimentally determined. This is achieved by connecting the sensor with a generator and an oscilloscope and generating a set of input values for the voltage and current and recording the output values of the sensor. The connection diagram can be seen on Figure 4.

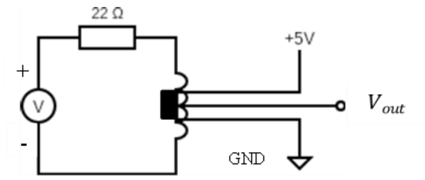

Fig. 4. Electrical scheme for determining mathematical model

We control the strength of the current flowing through the conductor through the generator, and we display and read the signal which we receive from the sensor on the oscilloscope. The experiment was done for current values from 0 to 1.4 Amps, and we write down the values for the corresponding generated voltage (Table 1), and with the help of software, in this case MATLAB, through the linear regression method we determine the dependence that best describes them. The expected dependence is the shape $y = ax + b$.

Table 1

V_{in} (V)	I (A)	V_{out} (V)
0	0	2.49
2.24	0.1	2.51
4.57	0.2	2.53
6.8	0.3	2.54
8.96	0.4	2.55
11.14	0.5	2.57
13.44	0.6	2.58
15.71	0.7	2.6
17.9	0.8	2.62
20.7	0.9	2.63
22.17	1	2.64
24.2	1.1	2.66
26.32	1.2	2.68
28.44	1.3	2.69
30.77	1.4	2.71

The obtained data from the software is graphically shown in Figure 5. The coefficient $\left(\frac{s\mu_0\mu_e}{2\pi r}\right)$ is calculated to be 0.15286 and the offset voltage to be 2.493, which is half of the input voltage as stated previously.

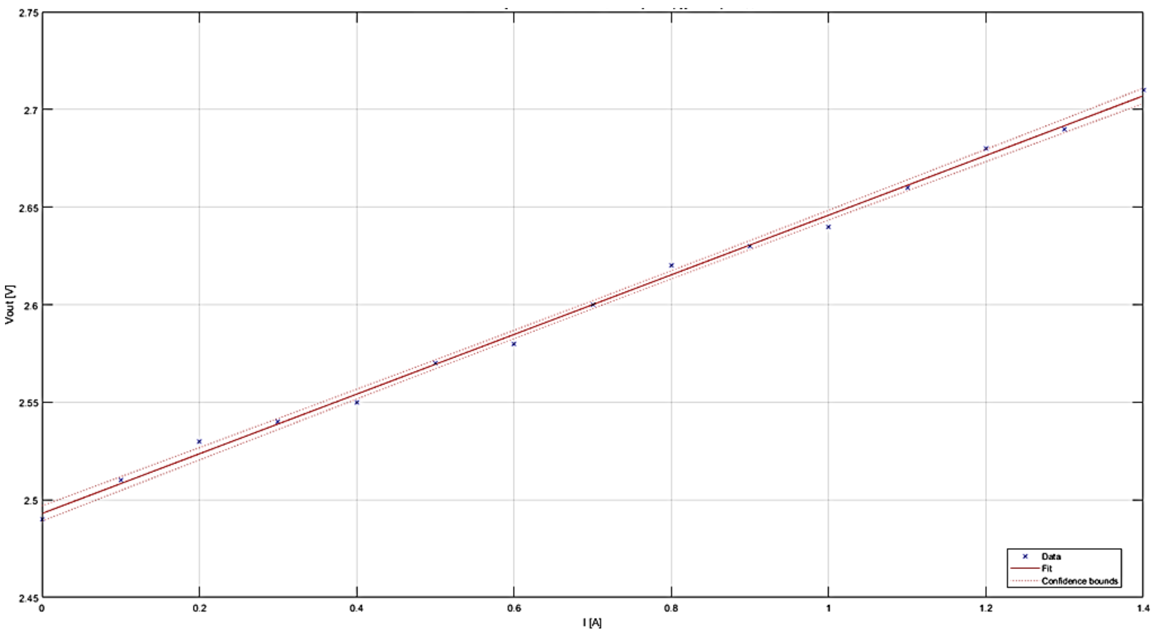

Fig. 5. Relation between the output voltage of the sensor and the current of the conductor

The final mathematical model for this system is described by equation 7.

$$V_{\text{out}} = 0.153 * I + 2.493. \qquad (7)$$

3. RESULTS AND DISCUSSION

After determining the coefficients of the mathematical model, the system is connected with a microcontroller which enables reading and writing of the data received from the sensor. The choice of microcontroller has a big role in the resolution of the system, i.e., the smallest possible change that can be detected depends on the microcontroller. Arduino UNO WiFi Rev.2 is be used for this project, which, as the name suggests, has a built-in WiFi module and can easily be connected to the Internet. The resolution of the system, or rather of the converter from analog to digital signal, can be determined by the equation 8:

$$ADC_{res} = \frac{V_{\text{ref}}}{2^{10}-1} = \frac{5}{1023} = 4.89\,\frac{\text{mV}}{\text{bit}}, \qquad (8)$$

where the value of V_{ref} indicates the power supply of the sensor and also the range of the output signal. The resolution of the sensor in the system is ~5 mV.

The system connection is the same as when determining the mathematical model (Figure 4), with the only difference that we do not connect the output signal to an oscilloscope, but to one of the analog pins of the Arduino, A0 shown in Figure 6.

After the device is connected to the Arduino, a program is created which will read the values from the sensor and transform them into useful data about the current passing through the conductor. We connect the Arduino to the Internet, and we upgrade the existing program with additional functions for sending the data to a cloud service. The cloud service we use is Blynk, an IoT (Internet of Things) platform for smartphones that is used to control various microcontrollers such as Arduino, Raspberry Pi and similar. The advantage of Blynk compared to other cloud services is the direct and easy connection to Arduino and the possibility of creating a simple user interface. To create a new application, it is necessary to create a template, i.e., template for how it would look, but existing ones can also be used. Templates mainly consist of dashboards, information about the connected system, assigning virtual pins, and of course, the appearance of the application. The appearance of the application is given in Figure 7.

The application can be accessed via a smartphone or the web. It shows the current measurement for the current and voltage, and values can be seen for hourly, daily, and monthly consumption. The program can be upgraded with conditions for sending notification to the user, as can be seen in Figure 8.

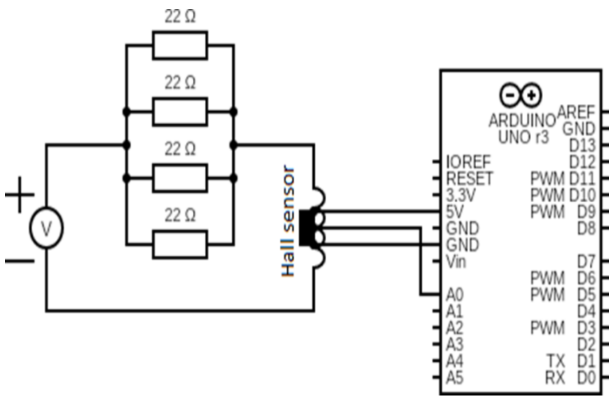

Fig. 6. Connection diagram of the current measuring system

Fig. 7. Blink application for the system

Fig. 8. Notification from Blink application to smartphone

Emphasizing the rational use of electricity, the condition was set that when the device is turned on for a long period of time a notification is sent to the user. These conditions can be varied based on the need, for example a notification to be sent when exceeding a certain current consumption.

4. CONCLUSION

The aim of this work was to create a system for measuring flow and strength of electric current in conductors using a Hall sensor and it was successful realized. During the analysis and realization of the system, it was shown that the Hall sensor is a good option for this application, but not ideal, since an additional power supply is needed. The system is suitable for use in conjunction with a large number of devices. The created system, although functional, has its drawbacks. The main disadvantage is that it needs to be integrated within the device. This would make it difficult to change the sensor from one device to another however by integrating some of the elements in a smaller assembly, and powered by a battery, it is possible to significantly reduce the dimensions of the system, and at the same time to allowing the system to become portable. Upgrading the device will mean coming closer to the standard current clamp for measurements only having smaller dimensions as well as an IoT application for real time monitoring of the devices we connect too.

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