American Journal of Applied Sciences and Engineering | *ISSN 2766-7596*
Published by ACADEMIC INK REVIEW | *https://airjournal.org/ajase*
12011 WestBrae Pkwy, Houston, TX 77031, United States
airjournals@gmail.com; enquiry@airjournal.org

Design and Implementation of a Close-Loop Hall Effect Sensor for the Measurement of Instantaneous Current and Voltage

[1]Eke, James, [2]Okafor, Patrick Uche, [3]Arinze, Stella Ndidi

[1, 2 & 3] Electrical and Electronic Department
Enugu State University of Science and Technology

Publication Process	*Date*
Received	***May 15th, 2021***
Accepted	***June 2nd, 2021***
Published	***June 30th, 2021***

ABSTRACT

The growth of every economy relies heavily on the availability and proper management of electrical energy in industrial and domestic applications. This growth necessitated the need for efficient and accurate measurement of electrical energy. In this paper, the principle of Hall Effect was deployed in the design and implementation of a low-cost close loop Hall Effect sensor for measuring instantaneous current. The output of the measurement is visualized through an LCD and can be interfaced to a PC for real-time graphing. The calibration result showed that the developed system has a relative error of 5.30% and can measure up to ±127.39 Ampere.

Keywords: *Flux Density, Hall Generator, Instantaneous Current, Magnetic Field, Hall Effect Sensor*

1. Introduction

Electrical energy is one of the major driving forces for various domestic and industrial applications, its importance cannot be overemphasized. It could be easily said that the growth of every industry lies heavily on the availability of electrical energy. Because of its importance, energy needs to be efficiently and accurately measured as much as possible. There are basically three types of electrical energy meters namely; electro-mechanical, electronic and smart energy meters. The electro-mechanical induction meter is a conventional type of electrical energy metering. It operates by counting the revolutions of a non-magnetic, but electrically conductive metal disc which is made to rotate at a speed proportional to the power passing through the meter. Effectively, the number of revolutions is proportional to the amount of energy consumed. The electronic meters display the energy used, and some types of the meter can transmit readings to remote locations. In addition to measuring the energy consumed, electronic meters can also record other parameters of the load and supply such as instantaneous and maximum rate of usage demands, voltages, power factor and reactive power used etc. They can also support time-of-day billing, for instance, they can record the amount of energy used during on-peak and off-peak periods. Smart energy meters have the capability of full-duplex communication. They can transmit the data to the utilities like energy consumption, parameter values, alarms, and can receive information from utilities such as automatic meter reading system, reconnect or disconnect instructions. Also, they can carry out some system software upgrades. These meters reduce the need to visit the meter location while taking or reading the monthly bill.

Many researchers are continuously carrying out works on how to develop a better approach in resolving issues associated with the conventional energy meters available for domestic and industrial use. Samson et al., (2014) introduced a new technology for “Home energy consumption measurement” having auto-calibration facility. In their technique, the Hall effect sensor was wirelessly attached to the output of the circuit breaker in the distribution panel. The accuracy of the system and gain error was improved through the use of high precision current transformer sensor. Austin, (2009) promoted the smart metering technology for energy measurement scheme using the AD516X family of electronic energy measuring Integrated Circuits (ICs). Those devices digitized the instantaneous values of voltage and currents with a high resolution.

A technology called Automatic Meter Reading (AMR) has been used to access data remotely via a communication link. AMR was replaced with Advanced Metering Infrastructure (AMI) by the authors to transmit data wirelessly. In the next advancement, the AMR was replaced by AMI (Advanced Metering Infrastructure) to transmit data wirelessly. AMI and smart technologies improve the energy efficiency as well as reduction of carbon emission. Liu et al., (2014) introduced the “offset error reduction technique for open-loop Hall effect current sensor”. In their work the novel method proposed for the minimization of the offset error was carried out. The accuracy of the system is 0.5% with controllability of 0.2%.

Balasubramanian, (2009) introduced a new energy measuring scheme for mobile technology. Nowadays, mobile phones having multiple applications are very common to everybody. Saving the battery life of the energy measuring scheme becomes paramount. A protocol called ‘TailEnder’ minimizes the energy usage while meeting delay tolerance deadline specified by the user. But this protocol is yet to be implemented in the applicable operating systems with a simple Application Programming Interface (API) application. Fugita et al., (2013) introduced “Hall sensor in Smart energy metering for power quality improvement”. Harmonic distortion measurement was the prime feature of their developed system. The result achieved showed that the measurement of harmonics ranges from fundamental to the 25th harmonic order. Ulrich, (2009) carried out intelligent energy measurement using a smart meter that has high precision and reliability. Power line communication (PLC) technique was applied in the smart meter.

The semiconductor module ‘TERIDIAN’ having integral functions of temperature and phase compensation, manipulation detection and light fluctuation is applicable for three-phase electrical energy meters. It is obvious that conventional electrical energy meters are prone to many challenges such as the inability to measure both DC and AC power, incapability for handling complex and discrete waveforms and they are unable to measure energy within a considerable range of error with better accuracy of the system.

2. Theory of Work

Hall Effect: According to Poulomi and Abhisek (2012), when a current carrying conductor is placed into a magnetic field, a voltage will be generated perpendicular to both the current and the magnetic field. The principle is known as the Hall Effect. Figure 1 shows a thin sheet of semi-conducting material (Hall element) through which a current is passed. The output connection is perpendicular to the direction of current when no magnetic field is present, current distribution is uniform and no potential difference is seen across the output.

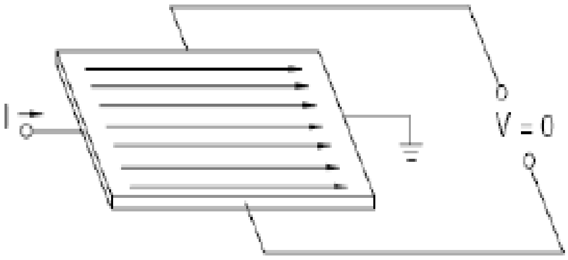

Fig 1: Hall Effect principle without presence of magnetic field (Poulomi & Abhisek, 2012)

When a perpendicular magnetic field is present as shown in Figure 2, a Lorentz force is exerted on the current. The force disturbs the current distribution, resulting in a potential difference (voltage) across the output.

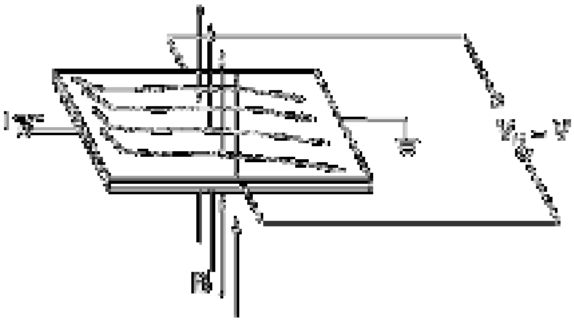

Fig 2: Hall Effect principle with presence of magnetic field (Poulomi & Abhisek, 2012).

This voltage is called Hall voltage (V_H). The interaction of the magnetic field and current is shown in the equation:

$$V_H \propto I * B \qquad (1)$$

The Hall Effect has two important properties: the possibility to measure constant and varying magnetic fields, and the ability to perform multiplication. It is a very powerful tool for the determination of the semiconductor material parameters. Linear Hall Effect Device which utilizes the principle of Hall Effect is an established theory in the field of current sensing, analysis of the presence of magnetic field and its strength. Here, a linear Hall Effect device is proposed to act as the main sensor part of the system that senses the change in magnetic field intensity and produces Hall Voltage which is proportional to both the applied magnetic field strength and the line current passing through the Hall Device (You & Chung, 2014). The power measuring system is compatible with both DC and AC (both 1-Φ and 3- Φ) measurement with discrete waveform including the presence of harmonics in the supply.

3. Methodology

This work proposed to use a closed-loop current sensor as shown in Figure 3. The magnetic core was designed and wound. The Hall generator was mounted in the air gap of a magnetic core placed around the current carrying conductor. The Hall generator was fabricated. The fabrication was done using thin films prepared by vacuum deposition of intermetallic compounds on isolating substrates. The semiconductor was formed to the desired shape by photolithography and etching. The electrodes were soldered to the copper wires. The conductor produced a magnetic field proportional to the current it was carrying. The magnetic core concentrates the magnetic field which was then sensed by the Hall generator together with its driving electronics. The Hall generator was encapsulated to protect it from light, humidity, dust, chemical corrosion and other environmental influences. Because the output of the Hall generator can be very low, it was amplified to a useful level (Poulomi & Abhisek, 2012).

The amplified Hall generator signal was used differently. Using a closed-loop design, this signal flows through the coils wound around the core at a pre-determined number of turns to offset the concentrated magnetic field in the core from the current carrying conductor.

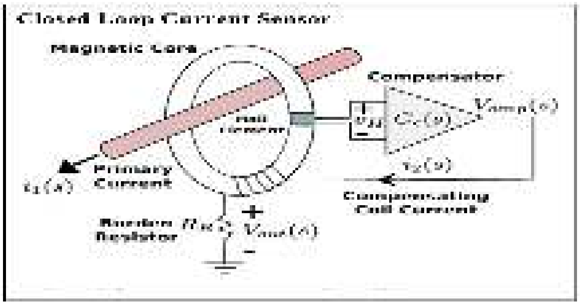

Fig 3: Closed loop Hall Effect Current Sensor.

The output measurement was basically the current it required to “null” the flux in the core, and it accomplished this by depending on the turns ratio of the coil around the core. This technique allows great improvements in sensor performance. The effects of magnetic core linearity as well as the effects of Hall generator linearity are practically eliminated by driving the core to nearly zero magnetic flux. On the other hand, this also eliminates the effects of temperature on the performance of the Hall generator. The resultant effects are low temperatures drifts, fast measurement response and higher quality linearity. Finally, the developed system was calibrated to make the measurement representation standard.

3.1 System Design

The concept based on Figure 4 is that instantaneous current can be deduced from the Hall Effect current sensor while the instantaneous voltage on the other hand is obtained from the potential transformer which is the voltage sensor. Thus, to deduce power, the instantaneous current and voltage are multiplied by electronic means. The major electronics components comprised of microcontroller, comparator, regulators, filters etc.

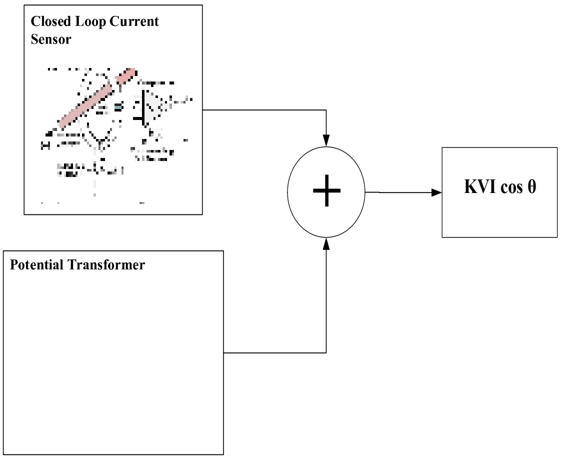

Fig 4: The schematic of the proposed model

From Equation (1), the magnetic flux density (T) is given as;

$$B = \frac{\mu_o \mu_r}{2\pi r} \qquad (2)$$

Where,
μₒ is the vacuum permeability ($4\pi \times 10^{-7}$/A), μ_r is the relative permeability, and I is the measured current (A). This magnetic flux density can be measured by a hall sensor. According to Dwitunggadewi, Panatarani and Made (2015), the magnetic field produced by current carrying conductor is usually very small thus, required a material with high permeability to strengthen the magnetic field, called a field concentrator. The field concentrators are basically used for boosting the flux density, positioning the sensor, and enabling closed-loop systems. The flux density is increased

with the effective permeability μ_r of the core usually has a typical flux amplification between a factor 20 and 70. It is obvious that without the concentrator, the position of the sensor against the conductor is highly dependent on the distance.

As shown in Figure 3, current *I* flow through the conductor wire. A hall sensor was placed into the toroid gap. The core and the hall sensor cross-section was made to have equal sizes. Works of literatures reported that the core area should be double the size of the hall sensor. The flux density that is produced by conductor wire was known by calculating the magnetic flux density using Equation (2). Since there was a gap in the toroid, the magnetic flux through the sensor change was calculated as follows;

$$B = \frac{\mu_o \mu_r I}{2\pi(r-d)+d\mu_r} \qquad (3)$$

Where d is the air gap. This equation can be rewritten in the same form as;

$$B = \frac{\mu_o \mu_e I}{2\pi r} \qquad (4)$$

Where μ_e as the effective permeability can be deduced as (Dwitunggadewi, Panatarani and Made 2015; Arya and Lizy, 2014; Gokmen and Tuncalp, 2010);

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

The output of the sensor which is a voltage can be represented as;

$$V_{out} - sB + V_{offset} = \left[\frac{s\mu_o\mu_e}{2\pi r}\right] I + V_{offset} \; (6)$$

Where s, is the sensor sensitivity. The bracketed quantities on the right of the equation are the constants. Thus the output voltage of the Hall Effect sensor is dependent on the current passing the wire.

3.2 Measurement

This work referenced the experimental setup presented in (Poulomi & Abhisek, 2012; Dwitunggadewi, Panatarani & Made 2015) as shown in Figure 5, where the constant current is passed through the semiconductor crystal to which a magnetic field was also applied. The force caused by a magnetic field affecting particles in the conductor creates an electric field that was measured as a voltage between the faces of the crystal. The effect exists in all carriers, but is much greater in semiconductors. This voltage, known as the Hall voltage, is proportional to the size of the magnetic field.

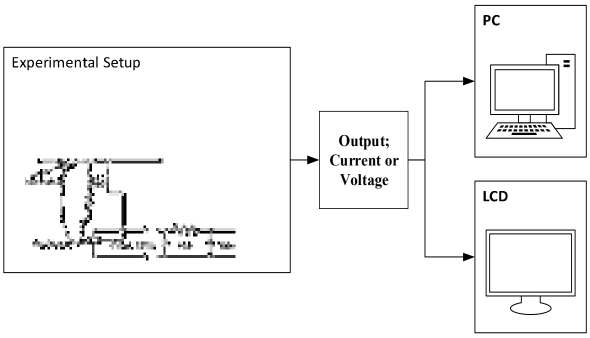

Fig 5: Measurement using Hall Effect Element

Experimental parameters from a published work by Dwitunggadewi, Panatarani and Made (2015) as presented in Table 1 were adopted.

Table 1: Experimental (Dwitunggadewi, Panatarani & Made, 2015)

Parameter	Value
Hall Effect Sensor Sensitivity	1.0 and 1.75 mV/Gauss
Magnetic Flux Linear	±650 G and ±1000 G
Relative Permeability (μ_r)	5000
Concentrator Diameter	Outer: 34mm; Inner; 9mm
Concentrator Thickness	16mm

From Table 1, the values of the relative permeability and dimension of the field concentrator were substituted in Equation (3). The achieved magnetic flux density for every 1 Ampere of primary current was 7.81 Gauss. The flux density was chosen in the range of ±1000 G using the SS49E sensor as a reference. To measure the current, it was deduced from the presented equation that the maximum current that can be measured was in the range of ±127.39 Ampere which was equal to ±1000 Gauss. The measurement test was limited to ± 40 Ampere for this experiment due to limitations in instruments for performance test setup.

The filter/signal conditioning circuit was designed to interface data to the ADC-10bit (V_{ref} = 5 Volt) and the Atmega 8535 microcontroller. Sensor sensitivity is taken to be 1.4mVolt/Gauss and offset voltage is 2.5 Volt from the SS49E sensor datasheet. The output voltage of the sensor was performed within the range of 1-4 Volt. This voltage range was converted to 0-5 Volt to serve as an input to the microcontroller, using LM7405 as a comparator with a voltage reference of 5 Volt. From the LCD, the value measured which is the output from the microcontroller was displayed through instruction codes. The resolution of the analog to digital converter (ADC) was achieved using (Dwitunggadewi, Panatarani & Made, 2015);

$$ADC_{res} = \frac{V_{ref}}{2^{bit}-1} \qquad (7)$$

Also, the resolution of current measurement was determined using (Dwitunggadewi, Panatarani and Made, 2015);

$$Current_{res} = \frac{1A}{1.92\ bit} \qquad (8)$$

Finally, the accuracy of the measured value was determined through the relative error between the measured value and the calculated value as follows;

$$Relative\ Error = \left|\frac{I_{measured} - I_{reference}}{I_{reference}}\right| \times 100\% \ (9)$$

4. Result and Discussion

Physical measurement was carried out without using a field concentrator, primary current of 1 Ampere with a radius of 8.5 mm produced a magnetic field of 0.24 Gauss, while with field concentrator, a magnetic field of 7.81 Gauss was produced. The sensitivity of the Hall Effect sensor was only 1 to 1.75 mV/Gauss. Perhaps, without a field concentrator, the Hall Effect sensor cannot sense the applied primary current as designed. The offset voltage of the Hall Effect sensor according to the datasheet is 1.7184 volt. Therefore, the essence of the signal conditioning was to change the input voltage into the desired offset based on the ranges of the measurement and the voltage reference of the ADC which was given as V_{ref} = 5 volt.

The resolution of the ADC was calculated to be 4.90 $\frac{mV}{bit}$ from Equation (7). Since 1 Ampere of applied primary current produced a flux density of 7.81 Gauss and on the other hand, the Hall Effect sensor sensitivity was 1.2 mV/G. The Hall Effect sensor produced an output voltage of 9.372 mV. Thus, the resolution of the current measured was also determined to be 0.524 $\frac{A}{bit}$ using Equation (8).

The accuracy of the current measurement carried out was determined, the difference between the measured current as displayed from the LCD and the calculated current from mathematical design produced the relative error. Using Equation (8), the maximum relative error in the proposed measuring system was 5.30%.

5. Conclusion

The design and implementation of close-loop Hall Effect sensor for measurement of instantaneous current and voltage was successful. The developed system was used to measure instantaneous AC current, and it can measure up to ±127.39 Ampere with a relative error of 5.30%.

References

Arya, K. S., and Lizy A., (2014). *IJISET*, 1(5), 380-386.

Austin, H. (2009). Smart metering technology promotes Energy Efficiency for a Green World, Analog Dialogue-43, 1-3.

Balasubramanian, N., Balasubramanian, A., and Venkataramani, A., (2009). Energy Consumption in Mobile Phones: A Measurement Study and Implications for Network Applications, IMC'09, Chicago, Illinois, USA, 1-14.

Dwitunggadewi, S., Panatarani, C., and Made I. J., (2015). Design and Development of DC High Current Sensor Using Hall-Effect Method. doi: 10.1063/1.4941871.

Fugita, S.D., Fernandes, R.A.S., Suetake M., and Da Silva I.N. (2013). Hall sensors applied as transducers to smart meters in the context of power quality, Innovative Smart Grid Technologies Latin America (ISGT LA), IEEE PES Conference, 15-17.

Gokmen, V., and Tuncalp, K., (2010). *Elec. Electrical Eng*. 5(101), 1-8.

Liu, C., Habil, I., and Liu, J.G. (2014). Offset error reduction in open loop Hall Effect current sensors powered with single voltage source, 978-1-4799-5643-2/14/ IEEE.

Patel, A. M., (2007). Current measurement in power electronic and motor drive application: a comprehensive study, M.Sc. thesis, University of Missouri-Rolla.

Poulomi, G., and Abhisek, M., (2012). Instantaneous Power Measurement using Hall Sensor. *International Journal of Scientific and Research Publications*, 2(8). 2250-3153

Samson, G.B., Levasseur, M.A., Gagnon, F., Gagnon, G. (2014). Auto-calibration of Hall Effect sensors for home energy consumption monitoring, *Electronics Letters*, 50(5), 403–405.

Ulrich, C., (2009). Intelligent Energy measurement, GF-S Special Projects, Hanau, Germany, 44-47. Available online: www. vacuumschemelze.com. last accessed: 3/11/19.

You, D., and Chung, K.S., (2014). Dynamic power management for embedded processors in system-on-chip designs, *Electronics Letters*, 50(18), 1309–1310.