Characterization of AC current sensor based on giant magnetoresistance and coil for power meter design

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Abstract. Electric current is the basic variable of measurement in instrumentation system. One of the current measurements had been developed was based on magnetic sensor. Giant Magnetoresistance (GMR) produces an output voltage when it detects the magnetic field from electric current flow. The purpose of this study was to characterize the response of GMR when variation number of coil was given. The characterization was the GMR voltage response to the AC current values from 0.01 A to 5.00 A. The linearity of the relation was reaching saturation point when the magnetic field measured higher than 10.5 Oe at room temperature. As the number of coil increased, the earlier saturation occurred. To see the sensitivity of the sensor response, the data graph was cut off at 1.56 A AC. From this research, we got single coil was ideal to measure electric current higher than 1.56 A AC, as the relation of GMR voltage to the current tended to maintain its linearity. For measurement of 1.56 A AC and less, coil number addition would increase the sensitivity of sensor response. This research hopefully will be benefit for further development using an electric current measurement based on GMR magnetic sensor for power meter design.

1. Introduction

Magnetoresistance (MR) basic principle is the material resistivity variation as a function of an external magnetic field [1]. The Giant effect of magnetoresistance itself was first reported by Baibich et al. in 1988 in measurement using Fe/Cr magnetic superlattice [2]. Giant magnetoresistance has advantages over other magnetic sensors. It has high sensitivity, high stability temperature, and has a minimalist size [3]. These advantages allows GMR to be applied in many areas, such as the use of GMR for Non-Destructive Test [4], GMR for navigation systems as a digital compass [5], and one of the latest research was the using of GMR sensor for sensor of Fe³⁺ concentration and flow rate [6] measurement.

One of the researches on GMR sensor in current measurement was for bare PCB inspection system [7]. As the review about GMR application mentioned that for specific electric current sensing, soldering the magnetic sensor onto a simple current PCB strip is the common way to implement a measuring system [1]. Another study was to use closed-loop to improve GMR sensor accuracy [8]. The research on current sensor based GMR chip also had been done [9] used a wire pass through a magnetic ring, a DC coil was uniformly wrapped around the magnetic ring and a GMR chip was placed in the gap of the magnetic ring. From that research the linearity of GMR output voltage to the current value known, with the sensitivity of GMR current sensor was 28.0064 mV·A⁻¹, the zero-current drift was 2.5319 mV, and the linearity was 0.99972 for the AC current range given.
In this research, we would to see GMR sensor response characteristic as power meter design development for the use in residential electrical power measurement. A 0.01 A to 5.00 A AC current range was given on the measurement with variation number of coil was set as the current medium. Here, we only focused on the measurement range and sensitivity response characteristic on GMR sensor.

2. Methods
GMR sensor used in this research was Integrated Circuit (IC) NVE AA002 series. GMR chip has a Wheatstone bridge configuration to convert magnetic signal into voltage signal [9]. In the chip formed four resistors, two were active sensing elements and two were shielded elements. The V+ input pin on GMR was connected to a 5 VDC voltage source, V- input pin was connected to GND, and both output pins were connected directly to the voltmeter.

The coil wrapped around GMR chip was a 0.5 mm diameter copper wire. Both ends of the wire were connected to 0.01 A to 5.00 A AC current source. On measurement, there was 1 to 8 variation number of coil for each of GMR response voltage data taken. The schematic of current sensor circuit shown in Figure 1 while Figure 2 shown the implementation of the schematic.

![Figure 1. (a) Current sensor circuit schematic, a is axis of magnetic sensitivity of GMR and b is magnetic field direction, (b) Current sensor circuit implementation from the schematic.](image)

We did this research on June until July 2017 at Instrumentation Laboratory, Physics Department, Faculty of Mathematics and Natural Sciences Education, UPI.

3. Result and Discussion
From the measurement we have GMR output voltage value relation toward 0.01 A to 5.00 A AC current graphic, shown in Figure 2.

![Figure 2. GMR voltage output relation toward giving current with coil number variation (I = 0.01 A to 5.00 A AC).](image)
The graphic has a linearity form and it became less linear proportionally with the addition number of coils. Coil number variation would affect the magnetic field value. For the same current value, increasing number of coils caused the stronger magnetic field detected. It also caused the earlier graphic data would reach saturation condition. In Figure 2, the data graphic of voltage to current relation for a single coil (N = 1) tended to be linear. In contrast with the using of 8 coils (N = 8) which has reached saturation point at 1.56 A.

The saturation condition happened due to the GMR characteristic. In GMR, the relation of voltage response sensor depends on measured magnetic field. Figure 3 shows the graphic of voltage relation toward magnetic field on GMR NVE AA002 chip in temperature variation, with the voltage supply applied to sensor was 5 V.

![Figure 3. Graphic of output voltage relation to magnetic field on GMR NVE AA002 chip. (NVE Corp., 2007)](image1)

In room temperature (25°C), the linearity of output voltage relation to magnetic field was within the range 1.5 Oe to 10.5 Oe [3]. While from Biot-Savart equation [8], the linearity would be generated from magnetic field toward the induced current, which magnetic value proportional to induced current. If magnetic field was linear to the current value, then the GMR output voltage can also said linear to the current through the linearity area according to the characteristic of NVE AA002 GMR sensor. If magnetic field detected by sensor was already over than 10.5 Oe, the graphic then became saturated.

The achieving of saturation condition also indicated the measurement range. For single coil data, the measurement range was further than using two coils and so. The increasing number of coils caused the shorter measurement range would be. For that reason, we were cutting the graphic at 1.56 A AC of 8 coils data (N = 8) which has a shortest range to see the characteristic of sensor sensitivity response, shown in Figure 4.

![Figure 4. GMR voltage output relation toward giving current with coil number variation (I = 0.01 A to 1.56 A AC).](image2)
The slope of graphic data shows the sensitivity of sensor response. In Figure 4 we have the sensitivity increased and have positive correlation to the number of coil addition. This occurred because increasing number of coils would make the larger magnetic field generated for the same value current given, as Biot-Savart law said the magnetic field has positive linearity relation to the induced current [10]. The sensitivity and linearity characteristic of the sensor from graphic in Figure 4 is written in Table 1.

Table 1. Sensitivity and linearity value on every coil variation (N = 1 to 8).

| N   | Sensitivity (mV.A⁻¹) | Linearity |
|-----|----------------------|-----------|
| 1   | 16.78                | 0.9721    |
| 2   | 38.99                | 0.9898    |
| 3   | 55.30                | 0.9953    |
| 4   | 80.08                | 0.9975    |
| 5   | 93.82                | 0.9838    |
| 6   | 106.54               | 0.9979    |
| 7   | 123.21               | 0.9874    |
| 8   | 125.89               | 0.9951    |

The sensor measurement accuracy could be determined by relation between the current and the value of the GMR output voltage. From Figure 4, if \( y \) represented the voltage \( V \) (mV) and \( x \) was the current \( I \) (A), we could have the equation of sensor measured current value. The percentage of measurement error had known with the using of Microcal Origin application. It is shown in Table 2.

Table 2. Equation and error percentage on every coil variation (N = 1 to 8).

| N   | Equation          | Error Percentage (%) |
|-----|-------------------|----------------------|
| 1   | \( I(A) = 0.06 V(\text{mV}) + 0.69 \) | \( 21.00 \times 10^{-2} \) |
| 2   | \( I(A) = 0.02 V(\text{mV}) + 0.29 \) | \( 6.08 \times 10^{-2} \) |
| 3   | \( I(A) = 0.02 V(\text{mV}) + 0.18 \) | \( 2.68 \times 10^{-2} \) |
| 4   | \( I(A) = 0.01 V(\text{mV}) + 0.13 \) | \( 1.21 \times 10^{-2} \) |
| 5   | \( I(A) = 0.01 V(\text{mV}) + 0.09 \) | \( 2.50 \times 10^{-2} \) |
| 6   | \( I(A) = 0.01 V(\text{mV}) + 0.08 \) | \( 1.07 \times 10^{-2} \) |
| 7   | \( I(A) = 0.01 V(\text{mV}) + 0.09 \) | \( 1.78 \times 10^{-2} \) |
| 8   | \( I(A) = 0.01 V(\text{mV}) + 0.08 \) | \( 1.31 \times 10^{-2} \) |

Linearity shows how ideal the relation between input and output measurement. In each number of coil variation there was a difference of measurement inaccuracy causing different linearity and error value. It was the result of GMR sensor that also measure the earth's magnetic field or magnetic field generated from nearby electronic devices when the measurement took place.

While the largest error value in single coil data occurred due to measurement below 0.70 A has not shown linearity characteristic yet. To put it more clear, Figure 5 was given as the separated single coil data graphic in relation between GMR voltage output and electric current given. The minimum value of current that GMR sensor could respond started in 0.2 A and the graphic has the linear condition when 0.7 A AC was given. In the GMR measurement characteristic from NVE Corporation [3], a linearity point begin when the measured magnetic field value of GMR was 1.5 Oe. It was possible that 1.5 Oe magnetic field value has not been reached yet when the current given was in 0.01 A to 0.70 A AC.
To anticipate the measurement error value, an additional magnetic probe can be placed close to the sensor, but out of the scope of the magnetic field generated by the current [1]. However, in this study the error value obtained was very small due to the coil position was very close to the surface of GMR, so the characterization we have done could said has an accurate result. As a suggestion, when measure the GMR voltage response to the current we also have to measure the magnetic field directly. It aims to know the value of the magnetic field generated by the coil more accurate.

4. Conclusion
We have successfully characterized the GMR response as an AC current sensor. The characteristic was relation of GMR output voltage toward current value if the variation number of coils were given.

The result showed the range of measurement would decrease as more number of coils added. It was due to the larger magnetic field generated for the same value current given, so the earlier the relation between voltage and current reached saturation point. To see the sensitivity characteristic, we cut the data graphic at 1.56 A AC which was the shortest point of the measurement range. We have sensitivity increased as the more number of coil variation given.

In conclusion, for measurement of small range current (1.56 A AC and less), the addition of coil number will cause the increasing sensitivity of GMR response. As for larger current measurements (higher than 1.56 A AC), the ideal coil have to use is a single coil because it tends to maintain its linearity and has a further range measurement. This research we have done hopefully will be useful for further development of power meter design using an electric current measurement based on GMR magnetic sensor.

5. References
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