Novel giant magnetostrictive material current sensor

Yan Shen¹, Zhao Liu, Qiuyan Lin, Jinming Ge, Guoqing Zhang and Wenbin Yu
Department of Electrical Engineering, Harbin Institute of Technology, Harbin 150080, China
E-mail: yanshen@hit.edu.cn

Abstract. Because of the shortcomings of the traditional inductive current sensor and optical current sensor, this paper proposes a new type of current sensor that uses a giant magnetostrictive material (GMM) to monitor and control power lines. This paper introduces operating principle and structure design of a GMM current sensor. To eliminate the frequency-doubled effect and to obtain good linearity, we set the bias magnetic field to 11.53 kA/m and the prestress force to 6 MPa. The strains of the 100- and 200-mm GMM sticks under the same magnetic field were compared; the results showed that the 100-mm stick had a larger strain. The magnetic field interference during a single-phase measurement of power lines was also studied. Finally, we analyzed the device sensitivity and discussed its influencing factors. The sensitivity reached $4 \times 10^{-9}$ m²/A.

1. Introduction
Using traditional current sensors to obtain an aperiodic current is difficult; the use of these traditional sensors can also be accompanied by the serious phenomenon of magnetic saturation based on electromagnetic induction [1]. Optical current sensors have therefore become the latest trend in current research [2, 3]. Optical current sensors, which compared with the traditional current sensors, enjoy the advantages of wide dynamic measurement range, no transient magnetic saturation, and strong ability to avoid electromagnetic interference [2]. Currently, however, the a magneto-optic glass is primarily used in sensing head of an optical current sensor, which is subject to the Faraday effects, leading to issues such as birefringence and temperature drift [3].

Two methods are thus clearly necessary so that these sensors can be improved: one method involves the complete replacement of the optical sensor technology, and the other method involves the application of a new functional material, e.g., a giant magnetostrictive material (GMM), which has been developed for years since 1970. In a GMM, the material size changes with the magnetic field intensity [4]. Compared with a normal magnetostrictive material, the GMM has the advantages of large magnetostriction coefficient, high-temperature adaptation, wide linearity range, smart response, and robust stability [5].

Owing to the many advantages of GMM, the application of this material involves a significant breakthrough for magnetism—e.g., sound-transform products [6]. Many of the early GMM applications involved long-range transmission sonar [7]. Currently, the applications for GMM include high-precision-speed micro-displacement actuators and large power low-frequency sonar systems,

¹ Address for correspondence: Yan Shen, Department of Electrical Engineering, Harbin Institute of Technology, Harbin 150080, China. E-mail: yanshen@hit.edu.cn.
among others [8]. In this paper, we report a type of current sensor which designed using a GMM and its application to monitoring of power lines. This sensor can convert the change in the magnetic field near a power line to a displacement of an output rod. When a fault occurs in the power line, such as a short circuit, which causes a dramatic change in the magnetic field, the output rod will trigger the circuit breaker to protect the line and adjacent equipment and prevent a large-scale blackout. The advantages of this device include the following: no outside energy source, no noise source, high speed, high precision, simple structure, and low cost.

2. Structure and operating principle

2.1. Structure of the GMM current sensor

The structure of a GMM applied current sensor is shown in figure 1. The current sensor consists of an output rod, a permanent magnet, a prestress mechanism, and a GMM stick. These devices are fixed in place by a shell, a rubber ring, a permanent magnet frame, and a pedestal.

![Figure 1. Basic structure of the GMM current sensor.](image)

2.2. Operating principle of the GMM sensor

Figure 1 shows that the GMM stick, shell, output rod, and pedestal form a closed magnetic path. A magnetic field alternately superimposes a biased magnetic field on the magnet. We place the device next to power lines, which causes the GMM to expand. The size of the GMM stick thus vibrates with a set response frequency because of the superimposed field, and the displacement resulting from a strain is transferred to others which called output rod. The displacement can acquiring or monitoring data, and it also can be directly applied as a protector. A set-up spring and a screw nut are included in the prestress mechanism comprises. This mechanism reduces the gap between the GMM stick and the output rod and amplifies the strain of the GMM stick that in order to achieve a satisfactory output. In addition, it makes the energy conversion of the device more efficiency.

3. Bias magnetic field and prestress

3.1. Bias magnetic field analysis

One property of the magnetostrictive effect is that its relative strain depends on the value of the magnetic field and not depends on its direction; thus, this strain can be expressed as $\Delta l / l = \psi (B^2)$,
where $l$ is the strain and $B$ is the magnetic field strength. Therefore this function can be considered as a quadratic function $\Delta l / l_0 \propto B^2$. According to the Hooke’s Law, $Tm$ is determined to be proportional to the strain; thus, $Tm = \gamma B^2$, where $\gamma$ is the proportionality factor and $Tm$ is magnetostrictive force. Once an alternating current with an angular frequency flows by a power line, the size of the ferromagnet would be also changes under the influence of the alternating magnetic induction intensity, i.e., $B = B_m \cdot \cos \omega t$, where $B_m$ is the peak value of $B$ and $\omega$ is the angular frequency. Thus, we obtain

$$Tm = \gamma B^2 = \gamma B_m^2 \cdot \cos^2 \omega t = (\gamma B_m^2 / 2) + (\gamma B_m^2 / 2) \cos 2\omega t$$ \hspace{1cm} (1)

The frequency of the $Tm$ is two times that of the input signal, a phenomenon that is called the frequency-doubled effect [3]. We often use a permanent magnet to induced a biased magnetic field $B_p$ to eliminate this effect.; thus

$$Tm = \gamma (B_p^2 + B_m^2 / 2) + 2\gamma B_p B_m \cdot \cos \omega t + \gamma (B_m^2 / 2) \cos 2\omega t$$ \hspace{1cm} (2)

In equation (2), $\gamma (B_m^2 / 2) \cos 2\omega t$ is the distortion part. This distortion part can be neglected when we set $2B_p \gg B_m / 2$; Namely, that effect can be eliminated in the case of that we set a more biased magnetic field than the magnetic field of the power line.

Furthermore, although the magnetostrictive effect of the GMM stick is non-linear, a large section in the characteristic curve exists that can be treated as non-linear because of the shape of the curve. Therefore, a biased magnetic field is setted can also make the operating point turn to the linear part.

3.2. Prestress analysis and biased magnetic field setting
The GMM characteristic curves would be various under different prestress settings. Once under axial prestress, the GMM can have higher energy transfer efficiency and a larger displacement output; thus, we can control the relationship curves between the magnetostriction coefficient $\varepsilon$ and magnetic field $H$ by choosing the prestress value. The experimental magnetostrictive characteristic curves obtained using a GMM stick (model Terfenol-D with 10 mm diameter) are shown in figure 2 (P1 indicates that the prestress is 1 MPa) [9].

![Figure 2. Experimental magnetostrictive characteristic curve.](image-url)
Magnetostrictive characteristic curves with different prestress values.

With respect to the experimental curves, a numerical fitting method using a magnetostrictive model of an exponential function plus a polynomial is used to obtain the following equation:

\[ \varepsilon = 165.776 P e^{-2.1612P/H} + (12 - P)(0.5928 + 3.655H - 0.1342 + 2.8667H^3 - 3.532 \times 10^{-5}H^4 + 2.57 \times 10^{-7}H^5 - 10.899 \times 10^{-9}H^6 + 2.4719 \times 10^{-12}H^7 - 2.3259 \times 10^{-15}H^8) \] (3)

Here, \( \varepsilon \) is the magnetostriction coefficient, \( H \) is the magnetic field strength, and \( P \) is the prestress value. We can obtain the characteristic curves under different prestress values by using this equation, as shown in figure 3.

Figure 3 shows that once the prestress reaches 6 MPa, the curve could exhibit a good linearity and a considerable magnetostriction coefficient when the magnetic field is in the range of 10–20 kA/m. Therefore, we choose 6 MPa as the prestress value. If we want the prestress force could be applicable to all working conditions, we should choose the screw nut and set-up spring as the prestress unit to clamp down the material to create the stress.

Using the characteristic curves, we set the biased magnetic field to be 10 kA/m. Then, according to equation (3), with \( B_p = 10 \) and \( B_m = 1.53 \), we decided that \( 2B_p \gg B_m / 2 \). Additionally, if we set the biased magnetic field to 10 kA/m, the operating point would in the middle of the linear part of the curve.

4. Material standard selection
A Terfenol-D (Tb0.3Dy0.7Fe1.95) GMM is selected in this study. We chose 10 mm as the diameter of the GMM stick and compared two sticks with lengths of 100 and 200 mm to determine which had a larger strain.

Because it is not parallel between the power line and the GMM stick, the magnetic field strength is not the same throughout the stick. Thus, the strain which applied on the stick is also not an average value. Therefore, calculating the average magnetic field strength on the GMM stick is essential to determine the strain on the entire stick. By assuming that the gap between the power line and the GMM stick is 0.1 m, the distance between the center of the stick and some points is \( x \), and the length of the stick is \( y \), the average distance between the power line and every point on the stick is

\[ r_{av} = \left( \frac{0.5y}{0} \int_{0}^{0.1} \sqrt{0.1^2 + x^2} \, dx \right) / 0.5y \] (4)
When the length of the GMM stick is 100 mm, the average distance between the power line and the
points on the stick is \( r_{av(100\text{mm})} = \frac{\int_0^{0.05} \sqrt{0.1^2 + x^2} \, dx}{0.05} = 0.104(\text{m}) \) according to equation (4). When the
length is 200 mm, the average distance is \( r_{av(200\text{mm})} = \frac{\int_0^{0.1} \sqrt{0.1^2 + x^2} \, dx}{0.1} = 0.1148(\text{m}) \).

We calculated the strain of the 100- and 200-mm standard GMM sticks when the current that flows
through the power line is 1000 A, 3000 A, and 40 kA; the results are listed in table 1.

From the results, it is a larger magnetostrictive coefficient in the 100-mm standard Terfenol-D stick.

### Table 1. Comprehensive results.

| Length | Item               | 1000 A | 3000 A | 40 kA |
|--------|--------------------|--------|--------|-------|
| 100 mm | Field strength     | 11.53  | 14.59  | 71.2  |
|        | (kA/m)             |        |        |       |
|        | Coefficient (ppm)  | 540    | 208    | 619   |
|        | Strain (mm)        | 0.054  | 0.028  | 0.062 |
| 200 mm | Field strength     | 11.386 | 14.158 | 65.45 |
|        | (kA/m)             |        |        |       |
|        | Coefficient (ppm)  | 527    | 188    | 602   |
|        | Strain (mm)        | 0.105  | 0.038  | 0.120 |

5. Magnetic field interference analysis

The primary factor that influences the precision is the magnetic field interference in practical
application. The other two phase currents will interfere with the measured phase; thus, the interference
must be analyzed when the device is moved to different positions.

![Figure 4](image_url)

**Figure 4.** Average magnetic field strength analysis without interference. (a) Relative position of the
GMM stick and the power line. (b) Average magnetic field strength curve.
5.1. No magnetic field interference

The relative positions of the power line and the GMM stick are shown in figure 4(a), and the average magnetic field strength curve that with no interference is shown in figure 4(b). The average magnetic field strength equation is

$$\bar{H} = \frac{L}{R} \arctan\left(\frac{0.5L}{R}\right) / \pi L$$

In this equation, L is the length of the GMM, I is the current on the power line, and R is the distance between the power line and the GMM.

Figure 4(b) shows that the average magnetic field strength exponentially decreases as R increases.

5.2. Interference from phase A

The relative positions of the power line and the GMM stick are shown in figure 5(a), and we can see that phases A, B, and C are aligned in a row with the same distance. The average magnetic field strength curves when phase A is measured are shown in figure 5(b). Distance $R_0$ is 1 m, and $R_x$ and $R_y$ denote the horizontal and vertical distances, respectively, between the phase A and GMM stick. We can conclude that when the GMM stick at a same height as the power line ($R_y = 0$), the average magnetic field strength curve approximates the condition without interference. However, when $R_y \neq 0$, the distortion of the curve is obvious, particularly in positions closer to the phase A line. The error in the magnetic field strength when phase A is measured originates from the other two phases when $R_y = 0$, as shown in figure 5(c); the relative error varies from 0.05 to 0.54.

Figure 5. Average magnetic field strength analysis when phase A is measured. (a) Relative positions of the GMM stick and power line. (b) Average magnetic field strength curves. (c) Relative error curves.

Because phases A and C are symmetrical, the interference when phase C is measured is the same as that for phase A; therefore, additional analysis of phase C is not required.

5.3. Interference from phase B

The relative positions of the GMM stick and the power line are shown in figure 6(a), and figure 6(b) shows the average magnetic field strength curves of phase B. We can draw the same conclusion as that
drawn for phase A. The relative error curves are shown in figure 6(c), which clearly shows that the relative error when phase B is measured is much smaller because phase B is in the middle of the three phases, and the interference from phases A and C neutralizes each other. When $R_y = 0$, the relative error varies from 0 to 0.65, and when $R_y$ is fixed, with the distance $|R_x|$ increases, the error also increases.

Figure 6. Average magnetic field strength analysis when phase B is measured. (a) Relative positions of the GMM stick and power line. (b) Average magnetic field strength curves. (c) Relative error curves.

Figure 7. GMM characteristic curve.

6. Device sensitivity analysis
Sensitivity is indicated by the differential relationship of the variables; the derivative reflects the influence of the changes in the design variables on the target function [10]. We analyzed the sensitivity of the device to confirm the influence of the magnetic field on the output and set the strength of the coupling using follow-up subsystems to complete the design. To calculate the
sensitivity and to investigate the factors that affect it, we plotted the GMM characteristic curve, as shown in figure 7. By calculating the GMM output sensitivity, we can obtain the derivative of equation (3) and employ it at the operating point. The slope is $4 \times 10^{-9} \text{ m}^2/\text{A}$. This high sensitivity can be applied to the monitoring of power lines. Because the biased magnetic field and the prestress force are already set, the biggest influencing factor is the temperature. GMM is a ferromagnetic material; thus, magnetic hysteresis loss and eddy-current loss are inevitable. The heat caused by the losses will lead to a temperature rise, and the GMM will incur additional elongation, which lowers the device precision.

7. Conclusions
Because traditional inductive and optical current sensors have some shortcomings, this paper proposes a new type of current sensor that uses a giant magnetostrictive material (GMM) to monitor and control power lines. We also analyzed the biased magnetic field and set it to 10 kA/m, which eliminated the frequency-doubled effect and also moved the operating point to the linear part of the curve. In addition, the prestress force was 6 MPa, which led to good linearity and a high magnetostriction coefficient. Furthermore, we studied the magnetic field interference when a single-phase power line was measured, and the results showed that when the GMM stick was at the same height as the power lines, the lowest relative error was achieved. In addition, the relative error when phases A and C were measured varied from 0.05 to 0.54 compared with that of phase B, which varied from 0 to 0.65. The error increased as the distance increased. Finally, the sensitivity of the device was determined to be $4 \times 10^{-9} \text{ m}^2/\text{A}$; the factors that influenced this value have been discussed.

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