A Passive Optical Fiber Current Sensor Based on YIG

Jing Shao, Wen Liu, Cui-Qing Liu, and Duan Xu

Abstract—A research on passive optical fiber current sensor based on magneto-optical crystal and a new design of light path of the sensor head are presented. Both methods of dual-channel optical detection of the polarization state of the output light and signal processing are proposed. Signal processing can obtain the linear output of the current measurement of the wire more conveniently. Theoretical analysis on the magneto-optical fiber current sensor is given, followed by experiments. After that, further analysis is made according to the results, which leads to clarifying the exiting problems and their placements.

Index Terms—Faraday effect, optical fiber current sensor, polarization.

1. Introduction

At present, electromagnetic current transformer is widely used in power system with its sensing head based on the principle of electromagnetic induction. Its simple structure makes it highly dependable and indefectible. However, the system may fail easily, which leads to various problems, including magnetic saturation, poor frequency response, electromagnetic interference, heavy equipment, difficult transportation and installation of equipments\cite{1},\cite{2].

Therefore, people shift their focus to optical fiber current sensor which has many advantages: (1) high accuracy over wide dynamic range, (2) wide bandwidth from DC to >100th harmonic, (3) light-weight and small size: excellent seismic performance; safe, easy, flexible, and cost-effective installation, (4) no CT saturation, and (5) safety & environmental benefits: no oil or SF6, no open secondary, no ferro-resonance, and galvanic isolation from HV line\cite{3].

2. Design of YIG Sensing Head

A new type of magneto-optical fiber current sensor is designed, the head of which is made of yttrium iron garnet (YIG). YIG material has various advantages, such as excellent crystal quality for high isolation, highly durability against abrasion, humidity, high temperatures and other environmental factors. Compared with traditional crystal, YIG hysteresis is less distinct (see Fig. 1). Given the limited Verdet constant, a magnetic device is added around the magneto-optical crystal to strengthen its magnetic field and improve the measurement sensitivity of the sensor. This device is made from nanocrystalline alloy, which is featured with good magnetic property, moderate saturation magnetic flu, high permeability rate, low loss, etc. In addition, the device also enjoys the benefits of light weight and low cost. To make it smaller, a U-shaped design is adopted. Fig. 1 shows the design of the light path of the sensing head. Light sheds into reflector through collimator 1, then passes through half wave plate with 22.5 degrees, which is actually a polarizer of 45 degrees. After going into YIG, the polarization plane has a deflection via Faraday effect. After passing the Wollaston prism, it divides into two orthogonal light beam, then exports to a detector through the coupled collimator 1 and 2 and has signal processed at last. Two reflectors are used here to change light path, mainly because of the limited size of magnetic device’s gap. Assuming the incident light intensity is \( P = E_i^2 \) and the angle of light deflected in magneto-optical medium is \( \theta_r \), then the output intensity will be

\[
P = E_i^2 \cos^2(\alpha + \theta_r), \]

where \( E_i \) is the value of the electric field component of the incident light and \( \alpha \) is the angle between the direction of polarizer and analyzer. In order to obtain the greatest sensitivity for the change of \( \theta_r \), it can be set that

\[
\frac{\partial}{\partial \alpha} \left( \frac{\partial P}{\partial \theta_r} \right)_{\theta_r \rightarrow 0} = 0. \]

Then \( \alpha \) is 45°.

After polarizing beam splitters (PBS), two light beams will be obtained, as shown by

\[
I_1 = \frac{1}{4} E_o^2 \cos^2(45^\circ + \theta_r)
\]

and

\[
I_2 = \frac{1}{4} E_o^2 \cos^2(45^\circ - \theta_r).
\]

Then we can put them into the equation

\[
\frac{I_2 - I_1}{I_1 + I_1} = \sin 2\theta_r \quad \text{to get} \quad \sin 2\theta_r. \quad \text{Since the value of} \quad \theta_r \quad \text{is small,} \quad \sin 2\theta_r \approx 2\theta_r, \quad \text{it is easy to get the deflecting angle.}
\]
With this method the effect of the fluctuation of the light source can be eliminate.

As can be seen in Fig. 2, the repeatability of \( P \) and \( S \) polarized light is pretty good. According to the experiment results, the linear regression can be obtained in Fig. 3.

As can be seen in the Fig. 3, after calculation, the slopes of \( P_1 \) and \( P_2 \) are slightly different, so are the slopes of \( S_1 \) and \( S_2 \). Then the linear regression and the real curve are compared in Fig. 4.

3. Experimental Analysis

3.1 Analysis on Direct Current Experiment

Power meter is used here to detect the output light power. Through the steady power supply changes, the power of the \( P \) and \( S \) polarized light can be detected and recorded respectively, as indicated in Fig. 2.

Fig. 2. Result of the detection.

In Fig. 2, \( I \) stands for current, \( G \) represents for magnetic field, which causes the Faraday effect. \( P_1 \) and \( P_2 \) indicate the two results of the power of \( P \) polarized light, and \( S_1 \) and \( S_2 \) are the results of the power of \( S \) polarized light.

To get the linear error, the measurement results can be calculated through:

\[
\text{error}_{P_1} = \frac{y_{P_1}(I) - P_1}{P_1}, \quad \text{error}_{P_2} = \frac{y_{P_2}(I) - P_2}{P_2}
\]

\[
\text{error}_{S_1} = \frac{y_{S_1}(I) - S_1}{S_1}, \quad \text{error}_{S_2} = \frac{y_{S_2}(I) - S_2}{S_2}
\]

as shown in Fig. 5.

Fig. 5. Analysis on the linear error.

To get the repeated error, the measurement results can be processed through:

\[
\text{error}_{\text{per}} = \frac{P_1 - P_2}{P_1}, \quad \text{error}_{\text{per}} = \frac{S_1 - S_2}{S_2}
\]

as shown in Fig. 6.
From the above analysis, the DC detection results at normal temperature are: the linear error reaches 2%, and the repeated error 1.45%. After excluding the effect made by the current source, the power meter, the gap of the magnetizer, the amplified spontaneous emission (ASE) light source and the disturbance of fiber, it can be concluded that the error results from the hysteresis of the YIG.

3.2 Analysis on Alternating Current Experiment

The data were collected from the sensor, and Table 1 and Table 2 show the results.

Table 1: Result 1 for AC measurement

<table>
<thead>
<tr>
<th>Real value of the current (A)</th>
<th>Measurement result minimum (A)</th>
<th>Maximum(A)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>11.89</td>
<td>11.96</td>
<td>about 0.6</td>
</tr>
<tr>
<td>25</td>
<td>23.8</td>
<td>23.89</td>
<td>about 0.3</td>
</tr>
<tr>
<td>50</td>
<td>47.6</td>
<td>47.7</td>
<td>about 0.21</td>
</tr>
<tr>
<td>75</td>
<td>71.35</td>
<td>71.5</td>
<td>about 0.2</td>
</tr>
</tbody>
</table>

Table 2: Result 2 for AC measurement

<table>
<thead>
<tr>
<th>Real value of the current (A)</th>
<th>Measurement result minimum (A)</th>
<th>Maximum(A)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>11.88</td>
<td>12</td>
<td>About 1</td>
</tr>
<tr>
<td>25</td>
<td>23.8</td>
<td>23.89</td>
<td>About 0.3</td>
</tr>
<tr>
<td>50</td>
<td>47.6</td>
<td>47.75</td>
<td>About 0.21</td>
</tr>
<tr>
<td>75</td>
<td>71.35</td>
<td>71.46</td>
<td>About 0.2</td>
</tr>
<tr>
<td>87.5</td>
<td>83.21</td>
<td>83.4</td>
<td>About 0.2</td>
</tr>
<tr>
<td>100</td>
<td>95.16</td>
<td>95.37</td>
<td>About 0.2</td>
</tr>
<tr>
<td>112.5</td>
<td>107.1</td>
<td>107.3</td>
<td>About 0.2</td>
</tr>
<tr>
<td>125</td>
<td>118.1</td>
<td>125</td>
<td>About 5</td>
</tr>
<tr>
<td>50</td>
<td>49.91</td>
<td>50</td>
<td>About 0.2</td>
</tr>
<tr>
<td>25</td>
<td>24.8</td>
<td>24.9</td>
<td>About 0.4</td>
</tr>
</tbody>
</table>

As can be seen from the measurement results, when the current is less than 125 A, the error remains small, and will decrease when the current increases in this range. Since the interference of noise will be relatively smaller compared with the larger current, the sine wave will be relatively good. Based on the results, to make sure the error is less than 0.5%, it is necessary to keep the smallest measurable current around 20 A.

In addition, the above-mentioned two tables demonstrate the contrast between the two measurements. When the current is less than 125 A, the repeatability is within 0.5%. When the current reaches 125 A, the error increases significantly to 5%. When the current is turned back to 50 A, since the measurement result is around 49.9 A, then the error is about 5%.

Therefore, the peak of 125 A of AC is about 175 A. The 175 A DC can generate, through the gap-magnetizer which is side-opening, a magnetic field of about 170Gs. At this time, the magnetizer shows no sign of saturation, so it is still in the linear area. And the resistance of the coil is proved to be good at the same time point. Thus, the increasing of measurement error which results in the drift phenomenon is caused by the characteristics of the YIG.

When the current is more than 125 A, YIG works in nonlinear area, and the internal structure of YIG already changes irreversibly, which finally results in lower accuracy. Then even when the current comes back to about 50 A, the measurement results can’t return to the original. That is, given the impact of large current, the repeated error of YIG can rise up to 5% or higher. Overall, the dynamic range of YIG is about 9 times, and the required dynamic range is 24 times or more. So the bottleneck we encountered now is that the dynamic range of YIG is too narrow, and the repeatability is too poor due to large current.

4. Conclusions

In this paper, both theoretical and experimental analysis are made around the U-shaped passive optical OCS, and the results are of significant reference and practical value. As above-mentioned, although the YIG sensing head has its advantages, it can’t be practically used because of its limited inherent characteristic. We hope to find a new type of material which has a wider dynamic range. But it needs to be further explored.

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References


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