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Application of an Optical Current Transformer For Measuring High Current

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Abstract

This paper examines the temperature characteristics of an Optical CT (optical current transformer) using the Faraday effect for measuring high current in a super high voltage-power apparatus. It is performed as follows by the sensor for embodying Faraday effect.

- A single-mode optical fiber capable of maintaining a polarization state is used.
- A light source is applied at 1310[nm] to a Laser Diode.
- The Linear of Faraday effect to a large current is evaluated and
- A possible application using an Optical CT was shown.

An Influence of Faraday effect to the surrounding temperature measured -40~50[℃], and the characteristic of the current sensitivity was reported. An application using the results of the temperature compensation system was used in order to compensate for surrounding temperatures. A possibility of applying Optical CT for electric power apparatus was advanced further. We were able to confirm that this temperature calibration method can minimize the fluctuation of the output signal depending on the temperature conditions.

Key Words : Magneto-Optical Current Transformer, Online Monitoring System, Laser Diode, Faraday Effect

1. Introduction

Recently, the demand for ultra high voltage power equipment increased in accordance with the rise of electric power capacity. Conventional type current transformers (CT) are used to meet the need for measuring capacities of large currents. These CTs are mainly used to measure the preliminary current by measuring the exciting current of the iron core by the magnetic field.

CT problems include their large size / heavy weight, distortions of the output signal due to the remaining magnetic field, and magnetic saturation. In spite of these weaknesses, the CTs were used extensively in order to measure the preliminary current and to protect the power network system. CTs serve the function of producing a large output

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signal (1[A]/5[A]) to operate the analogue relay. However, since the appearance of the digital power network systems, for example IEDs (Intelligent Electronic Devices) included the digital relay, there has been no need for the large output signal of the CT.

For these reasons, we propose using the non-conventional instrument transformer (NCIT), with Rogowski coil [1] and an optical sensor [2], to avoid the problems of the conventional type CT. Although there is no influence due to magnetic saturation or the remaining magnetic field in comparison with the CT, the NCIT using Rogowski coil does have its limitations - such as the sensitivity characteristic of fault current and the interference of phase relations[3]. Due to its compact size and lightweight, the NCIT can obtain a wide range of measurements using an optical sensor. The optical sensor has several merits, e.g. low loss, high insulation, non-induction, lightweight, and ease of repair[11].

The NCIT using an optical sensor has become an important tool for measuring the preliminary current in power apparatus. It has proved useful researching in a field test [4], and in a commercial application [5]. An optical current sensor can be divided by bulk type and optic fiber type according to the medium of the Faraday Effect.

- The bulk type optical current sensor, although it has high sensitivity because Verdet constant is high, cannot be used for measuring wide current regions due to the limitation of its polarized rotation angle.
- The fiber type optical current sensor (FOCS) can measure the wide current region with linearity due to the low Verdet constant. Also, it can control the sensitiveness by rounding several times around a conductor[6]. Although there are many projects in the world with these abilities, the influences of vibration and temperature remain serious problems[12].

We first report the measurement results of linearity characteristics for several 100 [A] depending on temperature. From these results, we obtain the temperature characteristics and propose the temperature calibration method for FOCS. For improving the sensitivity of preliminary current, this paper contains a detailed description of the signal processing method.

Contents

- Section Ⅱ contains a description of the basic theory, experimental equipment and procedure. Section Ⅲ contains results and a discussion of the sensitivity and the temperature calibration. Section Ⅳ contains a summary and conclusion.

2. Experiment

2.1 Faraday Effect

The Faraday effect is a phenomenon where polarized light rotates by effect of a magnetic field when light passes inside of magnetic substance. In Fig. 1, the rotation angle of a polarization side Θ that is relative to the magnetic field added to the substance was given by

$$\Theta = V \cdot H \cdot L \cdot \cos\phi \qquad (1)$$

where

V is Verdet constant in [rad/A],

H is a magnetic field in [A/m],

L is Faraday element's length in [m], and

ϕ is angle between the advance directions of light and magnetic fields in [rad].

A difference between the advance directions of light and the direction of magnetic field of zero is written

$$\Theta = V \cdot H \cdot L \quad (2)$$

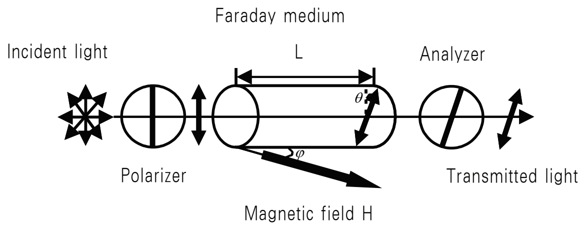


Fig. 1. Faraday Effect conception

With a bulk type optical current sensor, it is very difficult to measure the rotation angle Θ because of needing to detemine a vector value between directions of a magnetic field, and a transmitted light. To avoid this difficulty, we use the FOCS for the Faraday element. The rotation angle Θ is then proportional to the preliminary current and the number of a winding of an optical fiber based on Ampere's law and equation (2), given by

$$\theta = Vn \oint H \cdot dl = VnI \quad (3)$$

where n is the number of a winding of an optical fiber and I is current in [A]. Additionally, to minimize dependence on the temperature, we used the diamagnetic materials because they have a small Verdet constant and no relationship to temperature.

2.2 Experimental Arrangement

Experimental apparatus including the light source

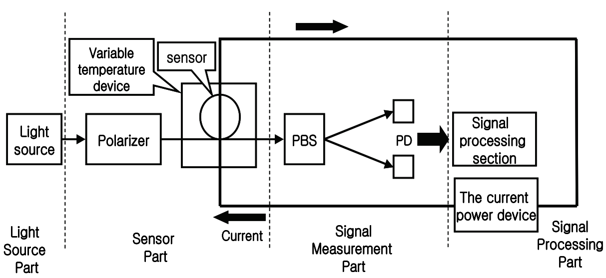


Fig. 2. A schematic diagram of the experiment

part droved by E/O converter, the sensor part included in the preliminary current power device, the signal measurement, and the signal processing parts are shown schematically in Fig. 2.

We used a 1,310[nm] laser diode with 25[mw] as the light source. It can operate for 105 hours. The sensor section measured the preliminary current by using the Faraday effect. It was manufactured to improve the sensitivity by 20 times winding of the signal mode optical fiber. The optical fiber was twisted several times per meter in order to prevent the linear polarization due to the linear. The sensor part also included the preliminary current power device and a variable temperature device. The variable temperature device displays the environment of different temperature conditions. The light radiated from the light source part is transmitted to the sensor part in the inside of variable temperature device, using an optical fiber. A polarized light spindle of the transmitted light was rotated according to the magnetic field intensity. It measured every increase of 100[A] from 400[A] to 1,300[A]. Temperature was increased every 10[℃] from -40[℃] to 50[℃] to simulate the operating condition of electric power apparatus. The signal measurement included the Polarization Beam Splitter(PBS) to separate two orthogonal vector ingredients. It has the function of converting from an optical signal to an electrical signal. The optical signal from the sensor part can be changed quickly and responsibility to an electrical signal using Photo Diode(PD)[7].

Finally, the signal processing part receives the signal from PD in real time and conducts the analysis and storage at the same time using a 16bits DAQ board and a LabviewTM commercial program. The LabviewTM commercial program performed the function of calibrating the temperature in house code.

2.3 Adaptive signal process

The signal processing circuits used in optical current sensing systems generally have to retain the fundamental functions of measuring the quantities of the Faraday rotation, filtering the signal to enhance the SN ratio, and amplifying the output signal.

Although Faraday rotation is in proportion to the preliminary current as eq.(3), the non-linear relation between the Faraday rotation and preliminary current exists because the amount of output is affected by the fluctuation of intensity caused by the optical sources. Three conventional signal processing schemes were developed and utilized in the optical current sensing system because of this: a difference scheme, a difference divided by sum(-/+)scheme[8], and an improved difference divided by sum scheme[9].

In the Fig. 2, two output signals of PBS can be illustrated with eq(4) and eq(5).

$$J_a = \frac{J_1 e(t)}{2}(1+\sin 2\theta) + n_1(t) \tag{4}$$

$$J_b = \frac{J_2 e(t)}{2}(1+\sin 2\theta) + n_2(t) \tag{5}$$

Where,

- J_a and J_b are two output signals of PBS,
- J_1 and J_2 are the optical intensity of transmitted light,
- e(t) is fluctuation of optical intensity, and
- $n_1(t)$, $n_2(t)$ are the noise in optical circuit.

The DC ingredient is given by $\frac{J_1}{2}$, $\frac{J_2}{2}$ and the AC ingredient can be expressed as

$+\frac{J_1}{2}\sin 2\theta$, $-\frac{J_2}{2}\sin 2\theta$

Fig. 3. shows a difference scheme of a simple electronic circuit part for the simplest signal processing.

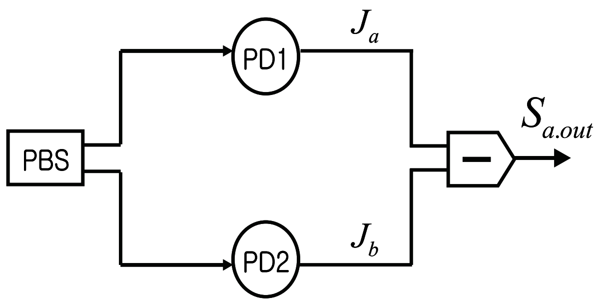


Fig. 3. The difference scheme diagram of the signal processing

$$S_{a.out} = J_a - J_b = \frac{J_1 e(t) - J_2 e(t)}{2} + \frac{J_1 e(t) + J_2 e(t)}{2}\sin 2\theta + [n_1(t) - n_2(t)] \tag{6}$$

If we suppose that two signal outputs of PBS are equal to a special constant, expressed as $J_1 \approx J_2 = J_0$, and, if the noises of light which pass through the optical circuit are same, it is approximated by $n_1(t) \approx n_2(t) = n(t)$.

Therefore, eq.(6) can be changed to

$$S_{a.out} \approx J_0 e(t) \sin 2\theta \tag{7}$$

Secondly, T. Sato, who introduced the difference divided by sum(-/+)scheme, used the $S_{b.out}$ given by

$$S_{b.out} = \frac{\sin 2\theta}{1 + \frac{4n(t)}{J_0 e(t)}} \approx \sin 2\theta + \frac{2n(t)}{J_0 e(t)}\sin 2\theta \tag{8}$$

Finally, T. Sato, who described the improved difference divided by sum (-/+) scheme, used

$S_{c.out}$ which is given by $S_{c.out} = 2\sin 2\theta$ (9)

3. Results

3.1 Linearity to the Preliminary Current

It was possible to show the relationship between the output of the signal processing section in Figure 2 and the preliminary current expressed the magnetic field. Figure 4 shows the linearity of the output signal measured from 200[A] to 1,400[A] of the preliminary current at normal temperature. Values of $S_{a.out}$, $S_{b.out}$ and $S_{c.out}$ were obtained using an average calculation by eq (7), (8) and (9) after getting 10 iterations of the signal of PD1 and PD2 divided by PBS.. Error bars in the figure were determined as follows: the vertical error bars, which present the accuracy of the Faraday effect measurement, were limited by the standard deviation width of the measurement during 10 iterations, while the horizontal error bars, which present the accuracy of the preliminary current, were determined by the accuracy of the current measurement devices inside the current power device in Fig. 2. $S_{a.out}$, $S_{b.out}$ and $S_{c.out}$ are in proportion to increases of the preliminary current, and $S_{c.out}$ of eq (9) is more linear than the result of the other signal processing.

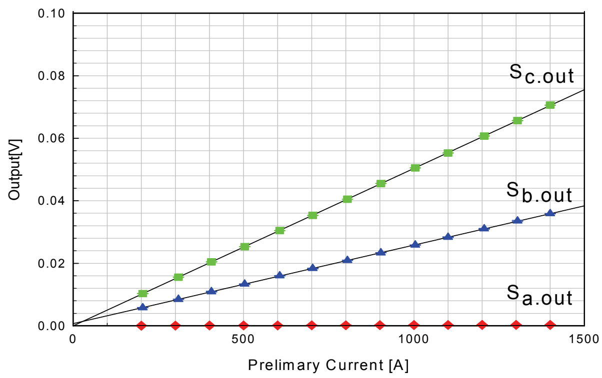
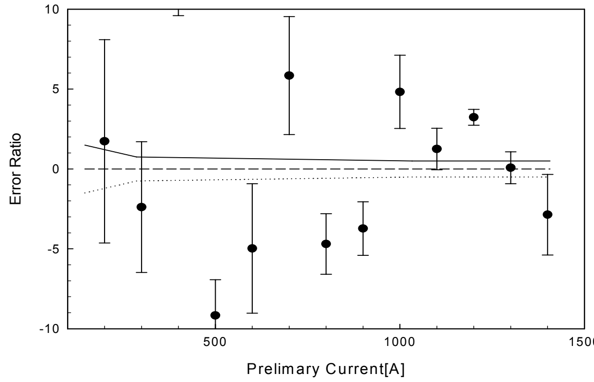
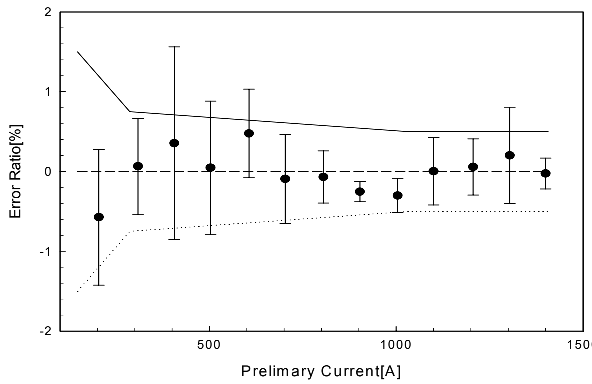


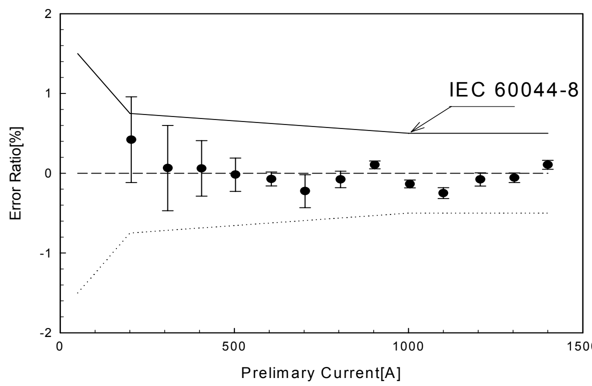
Fig. 4. The linearity of the output signal measured from 200[A] ot 1,400[A]



(a) difference scheme



(b) difference divided by sum(-/+) scheme



(c) improved difference divided by sum scheme

Fig. 5. A comparision of the error rate of the signal processing by eq.(7), (8) and (9)

We can obtain the fitting equations of $S_{a.out}$, $S_{b.out}$ and $S_{c.out}$ in Fig. 4. The values calculated by these equations could be determined the standard value. The mean of error ratio in the vertical axis is a deviation between the values calculated by the fitting equations and an average value of 10 iterations.. Figure 5 shows the accuracy of the Faraday effect measured for the adaptive signal process comparison with the standard value calculated above equations. The error bars for the horizontal were determined by the accuracy of the current measurement devices inside the current power devices in Fig. 2. The error bars for the error ratio were determined by the standard deviation of the measurement during 10 iterations. From these results, it can see that the error rate of $S_{c.out}$ in Fig. 5 (c) is satisfied with accuracy Class 0.5 in IEC 60044-8 standard[10].

3.2 Temperature characteristics

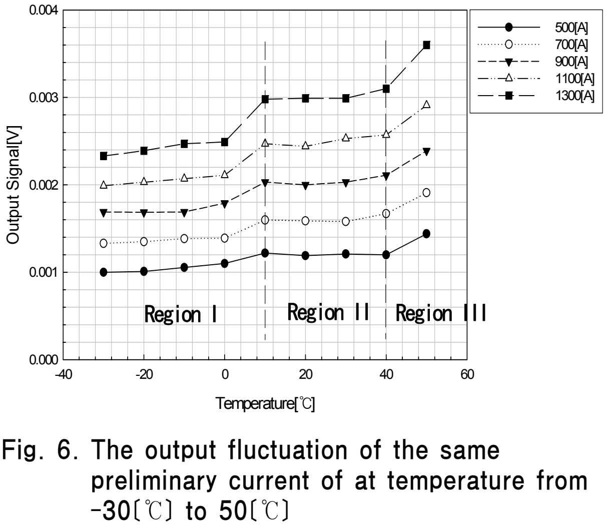


Fig. 6. The output fluctuation of the same preliminary current of at temperature from -30[℃] to 50[℃]

Fig. 6. shows the effect on temperature of installing an optical fiber sensor in a variable temperature device from -30[℃] to 50[℃], depending on the preliminary current. In order to obtain an average value, we measured 5 times for each temperature and preliminary current. The output signal was calculated by the adaptive signal process using Eq. 9. The value of the vertical axis in Fig. 6 is different than the value in Fig. 4 due to the power of the light source in Fig. 2.

From these results, it can be seen that the difference of output signal at the same preliminary current was attributed to temperature. The vertical error bar in Fig. 6 represents the accuracy of the output of the signal processing part, which was calculated using an average deviation, while the horizontal error bars, represent the accuracy of the temperature determined by the temperature sensor.

In figure 6, the amplitude of output is slowly increased according to the temperature in region I and the amplitude of output is similar to the temperature in region II. In region III, the amplitude of output is rapidly increased according to the temperature. From these results, we can determine that the Verdet constant of the optical fiber was dependent on the various temperature conditions and it was reason for using the calibration method for temperature condition.

3.3 Discussion : temperature calibration method

From measured output signals such as those shown in Fig. 6, the value of the rotation angle θ due to the magnetic field can be calculated by Eq.9. Using the Eq.3, we are able to determine that the fluctuation of the rotation angle θ on the same preliminary current was caused by the variations in the Verdet constant of the optical fiber depending on the temperature condition. In order to eliminate this fluctuation due to temperature, it is necessary to use a calibration method of these output signals against the temperature.

Thus we propose a temperature calibration method where a Verdet constant in regions I-II-III is multiplied with an appropriate ratio based on the constant with a temperature condition of 20[℃] in Fig. 6.

We used an experimental calibration method in the present case. The Verdet constant was based on one in region II. Verdet constants in region I /region III were multiplied with the appropriate ratio.

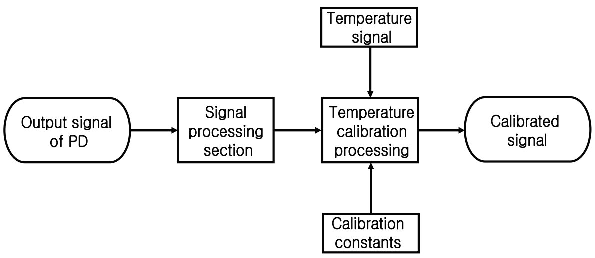


Fig. 7. A schematic diagram of the temperature calibration method.

Figure 7 illustates the temperature calibration method with measurement and calibration algorithms.

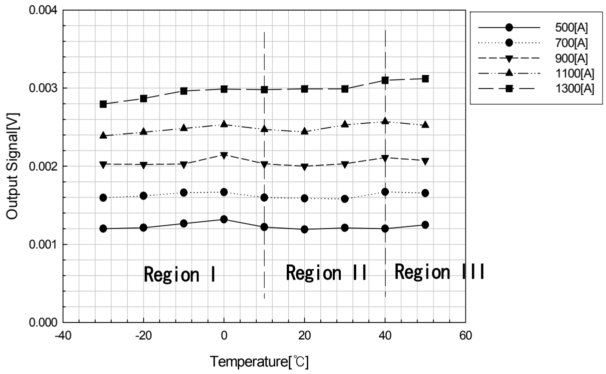


Fig. 8. The results calibrated against the variation of the temperature for Fig. 6

4. Summary

Using this temperature calibration method with house code software containing an algorithm calibration, the fluctuation of the output signal in Fig. 6 can be minimized as in Fig. 8. The error bar in Fig. 8 is the same as that in Fig. 6. Figure. 8 shows the Faraday shift as a fluctuation of the magnetic filed strength calibrated against the variation of the surrounding temperature for Fig. 6.

We conclude that this temperature calibration method allows one to minimize the fluctuation of the output signal depending on the temperature condition. Optical CTs in electrical substation facilities achieve significant reductions in unit dimensions and weight when compared to conventional electromagnetic induction CTs. Furthermore, the superb surge resistance performance of optical CTs allows for improvements in the reliability of equipment.

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