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Fiber Optic Measuring System for Electric Current by Using a Magnetooptic Sensor

KAZUO KYUMA, SHUICHI TAI, MASAHIRO NUNOSHITA, TAKASHI TAKIOKA, AND YOSHIAKI IDA

Abstract—A practical fiber optic measuring system for heavy electric current was developed by using the magnetooptic (Faraday) material. In order to obtain better SNR and smaller temperature dependence, the most suitable combination of the light source and Faraday material was experimentally and theoretically determined. Consequently, it was emphasized that an LED and diamagnetic SF-6 flint glass gave the superiority of overall system capability over LD's and para- or ferromagnetics. A novel type of fiber optic current sensor was constructed of the Faraday rotator of SF-6 flint glass with two thin-film polarizers. By using this sensor and a high radiance LED, high accuracy within ±0.5 percent was obtained for magnetic field between 20 and 500 Oe, and at temperatures from −25°C up to 80°C.

I. Introduction

A conventional technique for measuring the electric ac current in high-voltage power systems is based on inductive current transformers (CT's). However, with the recent growing demand for operating on higher voltage in such electric systems, the difficulty of isolation has sharply raised the production cost of CT's. For such demand, fiber optic current sensors are very promising because optical fibers are good isolators and suffer no electromagnetic interference.

There are some requirements for putting such sensors into practical use. With wide dynamic measuring range, the high accuracy within ±1 percent for operating temperatures from −20 to 80°C are required. Other requests for the sensors are small size, high reliability, and low cost.

Fiber optic current sensors are classified into the following three categories: 1) an interferometric sensor utilizing a single-mode fiber coated by magnetostrictive jacket [1], [2], 2) a sensor utilizing the Faraday effect of a single-mode fiber [3], and 3) a sensor constructed of a Faraday material and multimode fibers [4]. The major problem of types 1) and 2) is so sensitive to environmental variations such as temperature or pressure that they cannot satisfy the required accuracy.

In this work, the sensor of type 3) is developed. First, the optimum combination of the Faraday material and the light source is determined to obtain the required performances. Second, a novel integrated structure of current sensors constructed of thin-film polarizers and a Faraday rotator as one body is proposed. The principle and the basic performances of the current measuring system using this sensor are described in detail.

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II. Principle

Fig. 1 shows a schematic configuration of our measuring system. The light of constant intensity is guided from the suitable light source such as a light emitting diode (LED) to the optical current sensor through the incoming optical fiber. The sensor consists of two graded-index rod lenses (5.5 mm long and 1.5 mm in diameter), a polarizer, a Faraday rotator, and an analyzer. The light beam emitted from the incoming fiber is almost collimated by the graded-index rod lens and linearly polarized through the polarizer. The polarized direction of light is rotated in the transparent Faraday material under the influence of the magnetic field. The rotation angle φ is given by

$$\varphi = VHL \tag{1}$$

where V is the Verdet constant, L is the optical path length of the Faraday rotator, and H is the ac magnetic field generated by the electric current in a conductor. Since H is in proportion to the current, φ is also directly proportional to the current. Such polarization modulation due to the Faraday effect is converted into intensity modulation by using the optical analyzer. The maximum sensitivity and linearity of

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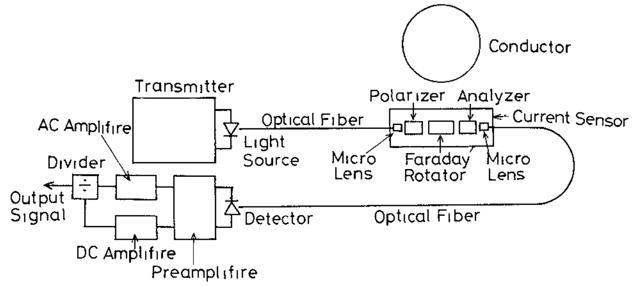

Fig. 1. Schematic configuration of the fiber optic measuring system for current.

measurement are obtained when the optical axis of the analyzer makes an angle of 45° with that of the polarizer. The intensity modulated light beam is coupled into the outgoing fiber via the other graded-index rod lens and guided to the photodetector. Consequently, the electric current (magnetic field) at the position of the sensor is remotely measured from output voltages of the optical receiver.

The light intensity P at the detector is expressed by

$$P = P_o(1 + \sin 2\varphi) \tag{2}$$

where P_o is the average light intensity at the detector. In the case of the optical receiver with a p-i-n photodiode, the overall noise level is equal to the sum of shot noise, thermal noise, and excess noise if the dark and leakage currents of photodiode are neglected. Then, the SNR (signal-to-noise ratio) of its output signal is written as

$$\frac{S_{p\text{-}p}}{N_{\rm rms}} = \frac{(mSP_o)^2}{2eBSP_o + \dfrac{4kTB}{R_L} + N_{ex}} \tag{3}$$

where S is the sensitivity of the photodiode, R_L is the load resistance of the detector, B is the bandwidth of the detector, m (=sin 2φ) is the modulation depth of the light dependent upon the current, e is the electron charge, and N_{ex} is the excess noise induced as the intrinsic noise or the modal noise when a laser diode (LD) is used. Equation (3) suggests that a higher radiance light source and a Faraday material with a larger Verdet constant are required to obtain the sufficiently high SNR.

It can be seen from (1) that all variations of P_o containing the source intensity, the transmission loss of fibers, the optical connector loss, or the insertion loss of the sensor causes the measurement error. In our measuring system, these errors are eliminated with the aid of an electric divider which normalizes the ac output signal ($\propto P_o \sin 2\varphi$) with the dc output ($\propto P_o$). The output noise originated from the electric divider utilized in this work (Teledyne Philbrick 4455) is sufficiently small ($\simeq$300 $\mu V_{\rm rms}$). Therefore, the serious degradation in the SNR of the normalized signal does not result.

III. Components

A. Faraday Materials

Generally speaking, all materials exhibit the magnetooptic (Faraday) effect, which is weak for diamagnetics and very strong for paramagnetics and ferromagnetics. The effect for diamagnetics is almost independent of temperature while paramagnetics and ferromagnetics have a larger temperature dependence on the effect. We fabricated three kinds of fiber optic current sensors with different Faraday materials, that is, Hoya SF-6 flint glass (diamagnetics), Hoya FR-5 glass (paramagnetics), and YIG (ferromagnetics) and measured their temperature dependence at the temperatures from −25 to 80°C. The features of light sources and optical fibers used in these experiments are shown in Table I, together with the Faraday material constants. Fig. 2 shows the variation of the output voltage in Fig. 1 with the temperature of the sensor. In these experiments, the sensors were placed inside a temperature-controlled climatic chamber, while the electronic processing circuits were outside it. The temperature was controlled cyclically between −25 and +80°C. The magnetic field was kept to be 50 Oe during the measurement. As shown in Fig. 2, the output variations in the temperature range from −25 to +80°C were approximately 30 percent and 25 percent for the FR-5 and YIG sensors, respectively. On the other hand, the SF-6 sensor has little variation within ±0.5 percent. For the conventional CT used in electric power systems, the measuring error within ±1 percent is usually required for the above temperature region. Therefore, the SF-6 flint glass is more suitable as the sensor material.

B. Light Sources

Fig. 3 shows a theoretical relationship between the magnetic field H and the average light intensity P_o required for the constant SNR. These curves were calculated from (3), assuming that R = 330 KΩ, B = 500 Hz, and N_{ex} = 0. As shown in Fig. 3, the magnetic field for the same SNR is decreased with increasing P_o.

Three kinds of light sources, i.e., AlGaAs-LED, single-mode AlGaAs TJS laser diode (S-LD), and multimode AlGaAs TJS laser diode with several oscillating modes (M-LD), were examined. When the LED (Mitsubishi Electric Corporation ME1203) with a self-aligned spherical microlens was driven with the current of 50 mA, the relatively high light intensity of about −12 dBm (=63 μW) was coupled into the multimode step-index fiber (core diameter: 100 μm and numerical aperture: 0.18). In the case of the S-LD and M-LD, the light intensities of 1.8 dBm (=1.5 mW) and −1 dBm (=0.8 mW) were coupled into the same fiber. It seems that LD's are now desirable light sources from the aspect of the light intensity.

When we determine the best light source, however, we have to take the excess noise N_{ex} into consideration as an important factor. In order to evaluate N_{ex} for the three light sources, we measured the noise characteristics against the driving currents and the light intensity at the p-i-n photodiode. Fig. 4 shows the relative noise level (N_l) in dBm as a function of the driving current of the light sources. The load resistance of the photodiode was 330 KΩ and the bandwidth of the following amplifier was 500 Hz. The light intensity P_o at the detector was kept constant to be −21 dBm by using an optical variable attenuator. The calculated noise level (N_c) neglecting N_{ex} is −44 dBm which is shown in Fig. 4 as a broken line. Therefore, N_{ex} is evaluated by (N_l-N_c) in Fig. 4. N_l of S-LD is maximum near the threshold current ($\simeq$28 mA) and decreases with increasing the driving current [5], [6]. N_l of M-LD (threshold current $\simeq$90 mA) is a current value of 8 dB

TABLE I
VERDET CONSTANTS OF THREE KINDS OF MATERIALS AND THE FEATURES OF LIGHT SOURCES AND OPTICAL FIBERS USED IN THE EXPERIMENTS

Material	Type of magnetics	Verdet constant (wavelength)	Light source (wavelength)	Optical fiber
SF-6 flint glass	diamagnetics	0.04 min./Oe-cm (0.87 μm)	AlGaAs-LED (0.87 μm)	multimode fiber (core diam.=100 μm, N.A.=0.18)
FR-5 flint glass	paramagnetics	0.11 min./Oe-cm (0.87 μm)	AlGaAs-LED (0.87 μm)	multimode fiber (core diam.=100 μm, N.A.=0.18)
YIG	ferromagnetics	9.0 min./Oe-cm (1.3 μm)	InGaAsP-LED (1.27 μm)	multimode fiber (core diam.=50 μm, N.A.=0.17)

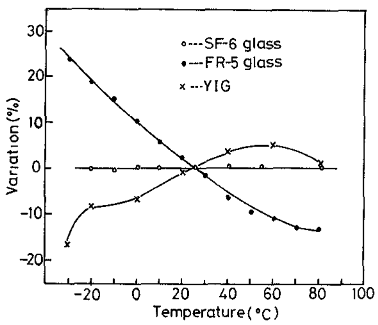

Fig. 2. Output voltage variation against temperature of the sensor for three kinds of materials.

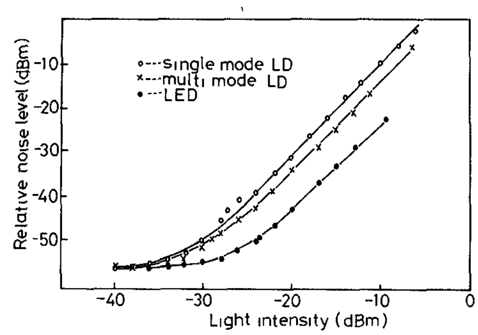

Fig. 5. Relative noise level as a function of light intensity at the detector.

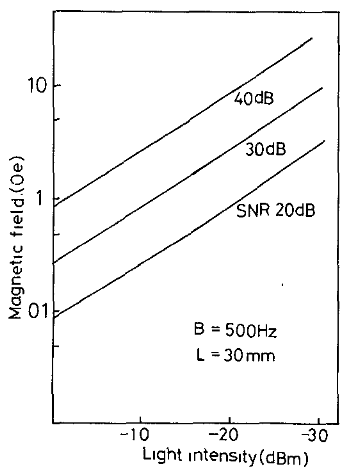

Fig. 3. Theoretical relationship between magnetic field and average light intensity required for the constant SNR.

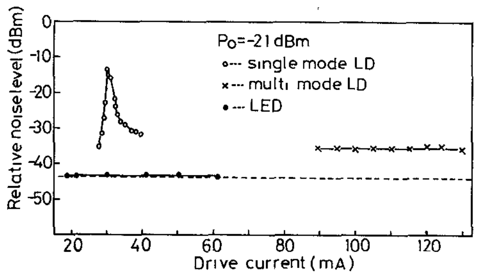

Fig. 4. Relative noise level as a function of driving current of the light sources.

above N_c. On the other hand, N_l of the LED is almost equal to N_c. These results show that N_l of the LED is dependent only upon the shot noise and the thermal noise, and that N_{ex} can not be ignored for S-LD and M-LD. Fig. 5 shows the relationship of N_l to P_o. S-LD was driven at relatively high light level (38 mA) to reduce N_{ex}. As shown in Fig. 5, N_l is almost independent of P_o below −33 dBm for all sources, and dominated by the thermal noise. For the LED, the shot noise becomes gradually predominant over the thermal noise as increasing P_o. On the other hand, the primary noise source of LD's is due to N_{ex} above P_o of −33 dBm, that is, the shot noise is neglected as compared with N_{ex} originated by both the intrinsic noise and the model noise. These phenomena mean that a further increase in the light intensity no longer improves SNR of the sensor system.

SNR was measured by using the fiber optic sensor with the Faraday rotator of the 30 mm long SF-6 flint glass. Fig. 6 shows the relationships between the obtained SNR and the magnetic field. SNR for the LD's is inferior to that for the LED in spite of the higher P_o. The theoretical curves including N_{ex} obtained from Fig. 5 are also shown by solid lines in Fig. 6. These curves are in considerable agreement with the experimental results. SNR for the S-LD is inferior to that for the M-LD because of its good coherency. As a result, a high radiance LED is determined as the most suitable light source for the fiber optic sensors.

IV. NOVEL TYPE OF FIBER OPTIC SENSOR

As described in the previous sections, the most suitable combination of the high radiance LED and the Faraday rotator of SF-6 flint glass is picked out.

A schematic configuration of our novel type of current sensor is illustrated in Fig. 7. The rotation angle φ of the polarization direction increases proportionally to the path length L of the Faraday rotator. However, from the aspect of SNR, the

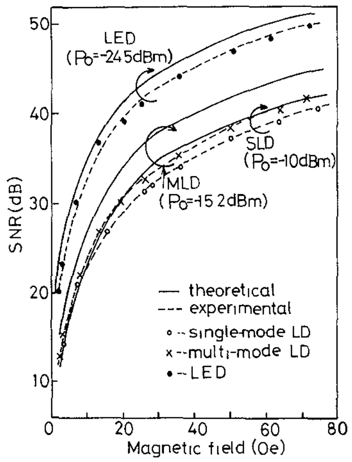

Fig. 6. Relationships between magnetic field and measured SNR of output voltages.

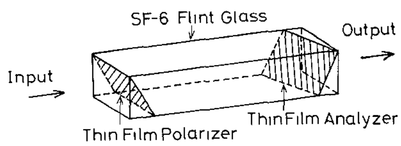

Fig. 7. Schematic configuration of the proposed current sensor.

optimum L is determined because the insertion loss of the sensor increases with L. From our preliminary experimental results, the highest SNR is obtained for L of 30 mm. The polarized prisms such as Glan-Thompson or Wollaston prisms are usually utilized as the polarizer and analyzer in Fig. 1 [7]. These prisms consisting of optically pure calcite or quartz are too expensive to put our sensors into practical use. In this work, two polarized beamsplitters of thin films are fabricated directly at both ends of the Faraday rotator of SF-6 glass, as shown in Fig. 7. First, a SF-6 glass block with 9 mm^2 (3 × 3 mm^2) cross section and 30 mm length was cut out in order that the relative angle between both end faces of the block might be 45°. After polishing the two end faces, the dielectric multilayered thin films were deposited on them by vacuum evaporation techniques. When these thin-film polarized beamsplitters were used as the polarizer and analyzer, their extinction ratio of about 10^2, which is large enough for our applications, was obtained at the wavelength of 0.87 μm. The available spectral width $\Delta\lambda_{PBS}$ ($\simeq$300 nm) of the fabricated polarized beamsplitters is so wide, as compared with the spectral width $\Delta\lambda_{LED}$ ($\simeq$45 nm) of the LED utilized, that the polarization fade-out problem with the LED source can be almost neglected.

The important parameter to evaluate the quality of the current sensor is the dependence of amplitude error and phase-angle error on the current. The overall deviation of the amplitude error in the 60 Hz magnetic field range from 20 to 500 Oe was within ±0.5 percent, while the overall variation of the phase angle error was within 50 min. Fig. 8 shows the frequency characteristics of the output deviation of the receiver. Since the Faraday effect has a very fast response to the magnetic field, the upper band limit of the measuring system is determined by that of the optical receiver [8]. As

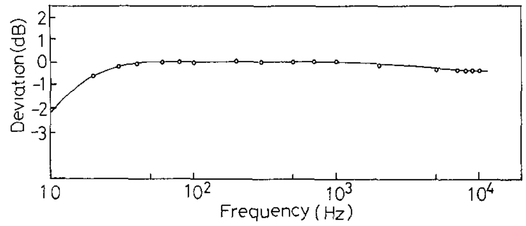

Fig. 8. Frequency characteristics of output voltage deviation.

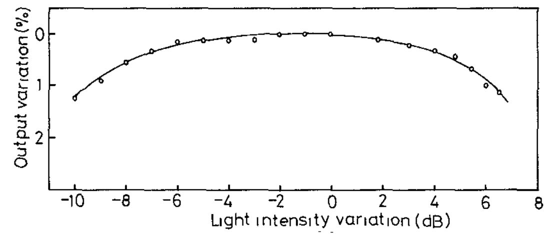

Fig. 9. Output voltage variation against light intensity variation.

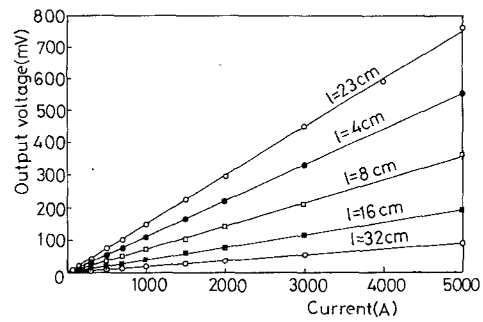

Fig. 10. Relationships between output voltage and electric current in the conductor.

the bandwidth of our receiver is about 10 kHz, the output level is constant for the frequency up to 10 kHz. The output variation of the receiver in the temperature range from −25 to 80°C was within ±0.5 percent. In Fig. 9, the variation of the output signal is plotted against the light intensity variation measured at the detector. The variation of about 16 dB in the light intensity is compensated within 1 percent with the aid of the electric divider described in Section II.

We measured the heavy current flow in the conductor by using our current sensor. Fig. 10 shows the relationship of the receiver output voltage against the current value up to 5000 A as a parameter of the distance between the conductor and the sensor. Linearity of the obtained curves is sufficiently good.

V. Conclusion

A fiber optic current sensor based on the Faraday effect was investigated. It was found experimentally that an LED and diamagnetic SF-6 flint glass gave the superiority of overall system capability over LD's and paramagnetics or ferromagnetics. That is, better SNR and smaller temperature dependence were obtained by using a high radiance LED and the Faraday rotator of SF-6 glass. A novel type of current sensor constructed of SF-6 flint glass block with the thin-film polarizer and analyzer at both ends was fabricated. The amplitude error within ±0.5 percent and the phase-angle error within ±25 min were obtained in the 60 Hz-ac magnetic field from 20 Oe up to 500 Oe. The accuracy within ±0.5 percent was obtained in the temperature region between −25 and +80°C. Thus, the performance of the fiber optic measuring system developed in this work is very superior to put to practical use.

We will make a plan to examine our fiber optic sensor to measure the heavy current in dynamically operating electric power systems in the near future.

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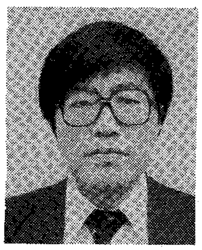

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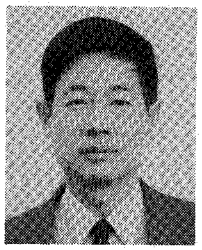

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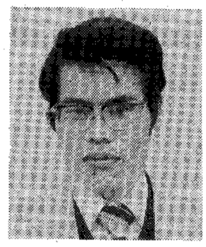

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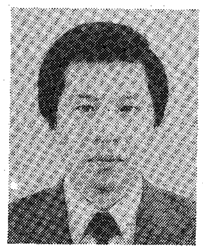

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