Fibre-optic current sensor exploiting Sagnac interferometer with Lyot-type fibre depolarizers

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Abstract. A Sagnac interferometer-type fibre-optic current sensor using single-mode fibre was proposed. To prevent non-reciprocal phase error, depolarizers are used in the Sagnac coil. This configuration makes the current sensor less costly and rather accurate. We fabricated the current sensor for an electric power substation by using the proposed technique and confirmed its characteristics. The dynamic range of 50 dB and ratio error within ±0.2% were satisfied. These results have demonstrated that the Sagnac interferometer-type current sensor using a single-mode fibre is suitable as an instrument for electric power plants.

1. Introduction

Until now, measuring current in electrical equipment was performed using a current sensor with an iron core and copper wire windings. By introducing high-performance protection systems and high-voltage power supplies, attention has been paid to current measurement using fibre-optic current sensors. This makes the size smaller because the sensor fibre is easily isolated. Moreover the environmental influence is minimized because insulating oil or SF$_6$ gas is not needed. Recently various fibre-optic current sensors have been proposed. In these sensors we think the Sagnac interferometer type fibre-optic current sensor [1,2] is the most promising because the technology used for fibre-optic gyroscopes can be applied without any change. It is highly reliable and applicable for electrical equipment. Nevertheless, the Sagnac loop is configured in the Sagnac interferometer-type fibre-optic current sensor using polarization-maintaining (PM) fibres. Using PM fibres require highly accurate axial alignment during fusion splicing, and installing the fibre-optic current sensor in a substation is complicated. Further, the PM fibres themselves are costly. Here, we propose a Sagnac interferometer-type fibre-optic current sensor, which enables fibre-optic transmission using a single-mode fibre. The basic concept is the same as that of a gyroscope using a depolarizer [3]. First the basic configuration and principles are shown. Next, the results of the characteristics tests are described. It was confirmed that the proposed current sensor has the accuracy required for application to electrical equipment.

2. System configuration

Using the scheme with counter-propagation of light, there is an opportunity to distinguish the birefringence-caused effects (for they are reciprocal) from the Faraday rotation-caused (this one being non-reciprocal). Although this scheme allows in principle to decrease the influence of the fiber birefringence, all the approaches, which are available now, failed to find an appropriate optical scheme to avoid strong reciprocal-effects-based errors. This problem can be solved by compensation of polarization noise with aid of spectral averaging of state of polarization (SOP).

The basic configuration of our fibre-optic current sensor is a Sagnac interferometer using the SM isotropic fiber-loop and depolarizers. A 1.55 µm super-luminescent diode (SLD) is used as the light
source. Light polarization, which is transmitted through the Sagnac loop, is a well-known source of noise. To suppress this noise, a highly accurate gyroscope is configured with a Sagnac loop using PM fibres. Meanwhile, a depolarizer is installed as a part of the Sagnac loop in the depolarized-type gyroscope, too. Light travelling through the Sagnac loop clockwise or anti-clockwise is depolarized to prevent noise due to polarization. This method is also applicable to fibre-optic current sensors. The first depolarizer is placed between the SM coupler and the multifunction integrated-optical chip (MIOC) to stabilize the amount of light passing through the MIOC. The depolarizer is of Lyot type. It is configured by fusion splicing two PM fibres with a 1:2 length ratio at 45° to the optical axis. To detect a phase difference due to the Faraday effect, light passing through the sensing fibre coil must not have polarization oscillating due to birefringence. Two fibre depolarizers are placed at both ends of the sensor fibre to obtain a stable SOP in average over SLD spectrum with a low degree of polarization (DOP).

The SLD used is \( \lambda = 1.55 \, \mu m \), and \( L_c \leq 40 \, \mu m \), and if the PM fibre beat length is 3 mm, \( \Delta \beta = 2000 \, \text{rad m}^{-1} \), and so it is desirable PM fibre length for a shorter arm of depolarizer \( L \) to be 15 cm or longer. In this experiment, \( L \) was \( \geq 50 \, \text{cm} \). The sensing fibre birefringence reduces fibre-optic current sensor sensitivity. According to the design, the maximum measured current is 100 kArms. Sensitivity can be improved by increasing the number of sensing coil fibre turns, but because of the constraint of the maximum measured current, a ten-turns coil is used. The fibre coil diameter is 200 mm. Even if the lengths of depolarizers and connecting fiber cable are added to this, the total length is less than 100 m. Then, as the time difference between the clockwise and anti-clockwise light passed through the MIOC is insufficient, sufficient modulation cannot be performed. To solve this problem, a compensating extra fibre coil, 400 m in length, was added. The extra coils are configured using single-mode fibres for 1.5 \( \mu m \) band.

The performance (accuracy specification) was tested according to IEC-60044-8 with a view to commercial production. The dynamic ranges of existing wound current sensors are narrow, and measurement has traditionally been performed using two-core current sensors, one for the control of small current, and one for the protection of large current. The accuracy classes most frequently used are 0.5 for control, and 5P for protection. Use of fibre-optic current sensors makes it possible to widen the dynamic range. With the proposed fibre-optic current sensor, the aim is to simplify the configuration to one sensor only from the existing two sensors by simultaneously satisfying the 0.5 class for control and the 5P class for protection using one sensor. The current sensors most frequently used in Russia have a higher error tolerance than the 0.5 and 5P classes, which are specified by IEC-60044-8, so that the proposed current sensor would be suitable for use in Russia, too. The rated frequency is thought to be 50 Hz.

3. Experimental results and discussion

The accuracy of the fibre-optic current sensor was measured in various environments to check the stability. The accuracy of the current and voltage metre used for electrical equipment is generally shown by ratio error, and can be defined using the following formula [4]:

\[
\varepsilon(\%) = \left[ \frac{(K_r U_s - I_p)}{I_p} \right] \times 100
\]

where \( K_r \) is the rated transformation ratio, \( I_p \) is the RMS value of the actual primary current and \( U_s \) is the RMS value of the optical current sensor output. Attention must be paid to the fact that \( I_p \) and \( U_s \) are the values of the actual current and not of the rated current. The ratio error is measured by an automatic instrument transformer test set by using a balanced bridge.

The measurement results are all within the ±0.2% range of ratio error, indicating that the fibre-optic current sensor has excellent linearity within ±0.2%, Fig. 1. The tolerable error of the 0.5 class sensor, which is defined by IEC 60044-8, is shown in the diagram using solid lines. The current sensors most commonly used for protection are those of this class in the world. The accuracy of the proposed fibre-optic current sensor satisfies the standards with sufficient margin.
The sensitivity of the fibre-optic current sensor is temperature dependent. The main reason for the sensitivity change is the temperature dependence of the SLD wavelength. As the temperature dependence of the SLD is about 0.2 nm K$^{-1}$, the SLD wavelength is shifted about 20 nm by the 100 K temperature change. The sensing fibre’s Verdet constant is proportional to $1/\lambda^2$ (where $\lambda$ is the SLD wavelength), and so 20 nm wavelength shift brings about 5% sensitivity change of the current sensor. To compensate for the temperature dependence of the current sensor, we install a semiconductor sensor to measure the SLD operating temperature. The signal processing unit has a ROM lookup table that memorizes data of the SLD operating temperature and the current sensor sensitivity. The signal processing unit calculates temperature compensated current data from GYRO circuit output and semiconductor sensor output. The temperature dependence of the Verdet constant of the sensing fibre is $0.69 \times 10^{-4}$ K$^{-1}$ [5]. It is also compensated by using a semiconductor sensor. The temperature difference of the sensor fibre and SLD operation temperature is designed to be less than 30 K. The sensitivity change of the fibre-optic current sensor because of the temperature dependence of the Verdet constant is less than 0.2%. After temperature compensation, the actual measured values are all within the ratio error range of ±0.2%, indicating excellent temperature stability.

Because fibre-optic current sensors are not subject to saturation such as iron core magnetic saturation, excellent linearity can be maintained even at large current. When the power systems are fully operational, they operate at the rated current for each system, for example, 4000 A, but if an accident such as grounding or a short circuit occurs, then the current is overloaded. As it is necessary to detect such current accidents, the fibre-optic current sensor must be able to measure the area up to 20 times of the rated value [6]. In the case of protection systems using a conventional wound current sensor, iron core saturation needs to be taken into consideration, and therefore, errors of 5% are tolerated for class 5P defined by IEC 60044-8.

The large-current experiment was performed also. The sensing coil is housed at the top of the magnetic polarizer. The electronic circuit is housed in a water-proof case at the ground potential. The sensing coil and electronic circuit are connected using a single-mode fibre. A maximum current of 100 kArms, which passes through the centre of the sensing coil using a shunt generator, is supplied to the conductor. The input current simulates the waveform in the event of a transmission line accident, and the waveforms in an exponential factor with a time constant of 0.03 s at an ac signal of 50 Hz are superposed. The input current was measured using a shunt resistor with excellent linearity even at large current. The top diagram shows the input current waveform, and the bottom diagram shows the fibre-optic current sensor output waveform. There is a good agreement between the two waveforms.
The ratio error between the waveforms is 1% or less, which is less than the 1% accuracy of the shunt resistor used for measurement. Linearity of the input–output characteristics of the current sensor up to 100 kA was examined by this measurement, but nonlinearity of the fibre-optic current sensor was not measured.

The dynamic range of the fibre-optic current sensor was 50 dB in the range from the noise level at 0 Arms of 10 Arms to 100 kArms. Therefore conventional two-core current sensors, which are used for control and protection by changing the sensitivity, can be replaced by only one fibre-optic current sensor. If the optical current sensor is used for ac measurement, then dc drift is not taken into account. But to measure the effects of non-reciprocal phase shift, the DC drift of the fibre-optic current sensor was measured. If a non-reciprocal phase shift exists, the dc component will be the output to the fibre-optic current sensor even if the primary current is zero, and this dc component will change over time. Such DC component changes were 10 Arms or less when measurement was performed for 1 h. This is 0.05 mrad when converted to phase difference. If non-polarization is insufficient, the polarized light will fluctuate due to birefringence changes, causing non-reciprocal phase shifts. These results indicate that the depolarizers are working effectively. Consequently, it was confirmed that the performance of the fibre-optic current sensor using single-mode fibre is equal to, or superior to, that of the previously reported fibre-optic current sensor using PM fibre.

4. Summary
We proposed a Sagnac fibre-optic current sensor using single-mode fibre, and checked its performance. It was demonstrated that error due to polarization fluctuations can be completely eliminated by using depolarizers. It is thought that the realization of single-mode fibre transmissions makes installation of fibre-optic current sensors easier and less costly. The input–output and temperature characteristics satisfied the ratio error within 0.2%. This performance is equal to, or superior to, that of the previously reported Sagnac interferometer-type fibre-optic current sensor using PM fibre. Considerable flexibility exists for tailoring the number of fiber turns on the sensing head to center the current sensing range around the customer’s desires. Fibre-optical current sensor design has evolved from the first prototypes made by RPC Optolink in 2007 [6], which in turn were a short design step away from the fiber optic gyroscope in production at RPC Optolink for commercial applications since 2002.

5. References
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