Hall effect current transformers (DCCT) that estimate current values from magnetic fields based on the Hall effect are widely used as current detection devices for fault selective equipment (50 FW) employed to protect feeding circuits in direct current (DC) substations for electric railway systems. In our development work, we have made efforts in developing a fiber-optic current sensor, with an aim of developing small and lightweight current sensors for DC that enable more precise measurement of circuit current. More precise measurement of line current will contribute to building more reliable power supply systems. Fiber-optic current sensors for DC were one of basic technologies that were studied in universities up to around 2000, and high-performance prototypes were successfully completed in a short period of time. We also obtained field test results for fault selective equipment using those sensors, indicating that they are sufficient to be put in practical application. This fiber-optic current sensor technology shows possibilities for a wide range of application in products.

**Keywords:** Fiber-optic current sensor, Faraday effect, Fault selective equipment, Hall effect current transformer

1 Introduction

In order to protect feeding systems for direct current electric railways, Hall effect current transformers (CTs) that measure direct current (DC) with flux density based on the Hall effect are widely used due to their high reliability and good response performance. But they have a disadvantage of causing minor errors due to magnetic field interference from adjacent circuit current, and improvement on that is needed. As another disadvantage of Hall effect CTs, we should point out that they need adequate space between each other to avoid magnetic disturbance when using two or more Hall effect CTs. That is a stumbling block to efforts to downsize them.

In order to solve these issues, i.e. to create a next generation CT that is more compact and resistant to affects of magnetic field interference, we have made efforts in development of a fiber-optic CT based on the Faraday effect. While there have been many approaches on fiber-optic CTs for alternating current (AC)\(^\text{1,2}\), and progress has been made in basic development for application to actual products for some of the approaches, it is difficult to apply them fiber-optic CTs to protect feeding for DC electric railways. Therefore, we have proceeded with the development of a fiber-optic current sensor by making use of a Sagnac interferometer that has shown excellent performance in the field of fiber optic gyro\(^\text{10,11}\).

In a series of experimental production and tests, we confirmed that our prototype fiber-optic CTs for DC have favorable characteristics for measurement of DC railway load current; and the results of field tests and verification tests in our laboratory showed that we are able to make measurements without being affected by magnetic field interference. We also proved by high current tests (short circuit tests) that fiber-optic CTs show effective performance even under both electrically and mechanically severe conditions when DC circuit breakers act.

2.1 DC Feeding System

For DC electric railways, feeder lines and contact wires are supplied with 1,500 V DC power that is rectified and stepped down from 66 kV extra high voltage at DC substations placed at intervals of several kilometers. As shown in the brief illustration of a structure of a DC substation in Fig. 1, nearby substations in a DC feeding system supply power to trains in parallel. Thus, it is important in case of short circuits or ground fault accidents at substations or on the track to immediately remove the problem circuit to avoid spillover of the accident and to protect facilities around the substation or the accident site. Today DC substations have systems that allow early detection of faulty current by constantly measuring current values of each circuit using a Hall effect CT. In this context, CTs play a very important role in protection systems; so, CTs require accuracy and good response performance as well as high reliability.
2.2 Conventional CT. (Hall Effect CT)

Fig. 2 indicates an example of the configuration of a Hall effect CT that is now widely used in feeding systems for DC electric railways. As shown in this figure, such a CT consists of iron cores around the current to measure and Hall elements that are placed in the space between iron cores, and it measures the magnetic field produced by that current using those Hall elements to determine current values. For example, a Hall effect CT of a configuration shown in Fig. 2 has a dual system built with the same structure on the right and left sides with two Hall elements on the upper and bottom sides, and each structure measures flux density. But, since such a CT measures flux density with four distributed Hall elements, the external magnetic field produced by adjacent circuit current not intended to be measured (e.g. current in DC bus in a DC substation for an electric railway or current carried in a adjacent circuit) can be an error factor for the CT. Instances of errors due to such magnetic field interference have been reported, such as minute current seeming to be carried even while a DC circuit breaker is open. Thus, more reliable measuring method is required on the field.

2.3 Developed CT (Fiber-Optic CT)

Development of fiber-optic CTs is intended to improve the weakness of Hall effect CTs that comes from measuring magnetic field with only a few distributed Hall elements to determine current values. It is also intended to create CTs that are resistant to affects from magnetic field interference by measuring the magnetic field as a continuous line integral value. Furthermore, fiber-optic CTs can be reduced in size and weight, giving them higher operability and constructability compared to Hall effect CTs. But what is most attractive when considering that substation facilities shall be more space-saving in the future and transitional peak current shall be higher is the characteristic that they are resistant to affects from adjacent-circuit current.

A fiber-optic CT measures magnetic field with the Faraday effect. This effect is based on the phenomenon whereby the difference between velocities of clockwise and counterclockwise circularly polarized light becomes larger in proportion to magnetic field intensity regarding circular polarized light. Regarding linear polarized light, on the other hand, this effect is based on the phenomenon whereby the inclination of polarization (angle of rotation of polarized light) \( \theta \), becomes larger in proportion to magnetic field intensity. Equation (1) is a general formula that indicates this characteristic of the Faraday effect. In the following formula, \( V \) is Verdet’s constant, \( H \) is the applied magnetic field, \( L \) is the light path length in the crystal, \( n \) is the number of turns of the fiber and \( I \) is the value of the measured current.

\[ \theta = VHL = nVI \] 

Fig. 3 shows the optical structures of the prototype fiber-optic CTs. In order to detect the arrival time interval due to the velocity difference of two circularly polarized lights caused by the magnetic field interference by the current to be measured, the CTs have Sagnac interferometers in their structures. Based on the difference in optical structures, we made prototype CTs that are (a) Loop type and (b) Reflection type. A photo of the prototype reflection type fiber-optic CT is shown in Fig. 4. In this figure, (1) is a sensor control box that accommodates a light source, light polarizer, fiber delay line, piezoelectric modulator and other equipment, (2) is a fiber transmission line that is not sensitive to magnetic fields, (3) binds a \( \lambda /4 \) element and a reflection mirror, and (4) is a sensing fiber. Table 1 summarizes main optical specifications of the sensor.

With a loop type fiber-optic CT, light from the source is polarized by a light polarizer, branched in two by a coupler, then each of the branched lights reach a \( \lambda /4 \) wavelength plate. The light that is circularly polarized there now goes backward in the optical fiber, and after being affected by magnetic field, goes through the \( \lambda /4 \) wavelength plate and the coupler again, and is interfered (by a loop Sagnac interferometer). The clockwise and counterclockwise lights that go backward in the optical fiber loop around the circuit to measure are positively and negatively affected due to the Faraday effect and that causes a phase difference.

In a reflection type fiber-optic CT, linearly polarized light by a light polarizer goes to a polarization maintaining fiber that is connected at a 45° torsion angle. The linear polarized light that is equally carried to the horizontal and vertical axes is, by a \( \lambda /4 \) wavelength plate, converted into circular polarized lights in the reverse rotation to each other (clockwise (CW) and counterclockwise (CCW)). Although CW and CCW lights go in the same direction, they are reversely affected by the Faraday effect from the magnetic field, and a phase difference occurs. This phase difference is interfered at the connecting point at a 45° torsion angle between a depolarizer and a polariz-
er and finally detected (by an in-line Sagnac interferometer). As shown in Equation (3), when the number of turns of the fiber winding around the circuit to measure is the same, the final phase difference detected by a reflection type CT is twice as large as that detected by a loop type CT. That is because the back and forth transmission length of a reflection type CT is twice as long as that of a loop type CT.

A loop type fiber-optic CT has an economic advantage that it needs no reflection mirror. On the other hand, a reflection type fiber-optic CT has advantages that it can be easily installed, that it has higher sensitivity because light goes and returns around the circuit and the light path length is twice as long as of a loop type with the same number of turns of the fiber, and that it is resistant to affects of mechanical vibration as proved in an experiment to be described below.

2.4 Performance Requirement for Fiber-Optic CT

A main measurement objective for fiber-optic CTs is circuit current supplied from substations in DC feeding systems. In order to protect feeding systems in the future, those CTs need to achieve the desired measurement accuracy and satisfactory reliability. Regarding measurement of usual load current, an early prototype fiber-optic CT developed in FY 2002 successfully showed measurement results with little difference from the results of a Hall effect CT. Still, improvement of the following items remained as an issue for putting them into actual use. Thus, we made required improvements in the process of the three-year development.

The first was improvement of the temperature characteristic. For example, for lines in JR East’s operation area, we expect the temperature in substations to be installed with fiber-optic CTs to be -10 to 40°C; so, those CTs must make stable measurement without zero point shifting even in such a range of temperature change. The early prototype CT was highly affected by temperature drift that was possibly caused by the temperature characteristic of the $\lambda/4$ wavelength plate, one of optical components. We improved on that by applying an integrated structure for optical fiber and a $\lambda/4$ wavelength plate by burn-in twist connection, which was already reported at that time as a structure with which a $\lambda/4$ wavelength plate is resistant to affects of temperature change. The second was improvement of response performance. In order to detect short circuits and other troubles and maintain safety, satisfactory response performance to transient change of current values is required. Specifically, considering application to wind type fault selective equipment that detects short circuit accidents, the current change of several thousand amperes within several tens of milliseconds (e.g. 3,000 A within 40 ms) must be detected. As present Hall effect CTs can detect current changes almost instantly, it is desirable to achieve performance close to that as possible. At the same time, in order to detect short circuits and other troubles and maintain safety, satisfactory response performance to transient change of current values is required. Specifically, considering application to wind type fault selective equipment that detects short circuit accidents, the current change of several thousand amperes within several tens of milliseconds (e.g. 3,000 A within 40 ms) must be detected. As present Hall effect CTs can detect current changes almost instantly, it is desirable to achieve performance close to that as possible.

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Last, but not least, was improvement of vibration characteristics. The early prototype CT was so easily affected by vibration that its output shifted when the fiber swung. That meant unpredictable mechanical vibration such as in earthquakes might cause operation errors, so, improvement was required. For example, in the field test of the early prototype, current pulse of around 1,000 A that was not actually generated was detected due to vibration by the operation of breakers for power outage (feeding stopped) at night. A reflection type fiber-optic CT to be explained below does not show such poor vibration characteristics. Hence, this type will achieve performance desirable for actual use, rather than loop type CTs.
For putting fiber-optic CTs into actual use, we carried out performance tests measuring high current that can occur in case of accidents in DC feeding systems and evaluation tests of the influence by adjacent circuit current. Those tests were performed using a high current testing device at the Research and Development Center of JR East.

3.1 High Current Test

Fig. 5 shows the results of a measurement performance test of current measurement with 20,000 A high current. The curves indicate the results for a conventional Hall effect CT, a saturable reactor type CT, a loop type fiber-optic CT, and a reflection type fiber-optic CT, listed in that order from the top. A saturable reactor type CT is a newly developed CT that is lightweight and resistant to affects of magnetic field interference.

The high-current test results proved that fiber-optic CTs achieved high current measurement performance equivalent to conventional Hall effect CT’s, with a little delay in response. But, for loop type fiber-optic CTs, tests indicated that measurement results were affected by mechanical vibration possibly caused by impact waves immediately after the conduction of high current. Such an instant mechanical impact can occur during the field use; so we decided to employ reflection type fiber-optic CTs in creating devices for actual use.

3.2 Evaluation of Influence by Adjacent Circuit Current

In order to identify influence by magnetic field interference of adjacent circuit current to the measurement performance of CTs, we placed CTs adjacent to circuits with load current level currents as shown in Fig. 6 and carried out a test to check the influence. Fig. 7 shows the outputs of CTs at around 3,500 A. In this case, as each CT measured no current, the outputs should have been 0 A; but conventional Hall effect CTs erroneously measured current around 400 A, and saturable reactor type CTs also measured current around 100 A. On the contrary, we found that the fiber-optic current sensor we developed received almost no influence.

On present Hall effect CTs, we cannot expect measurement resolution at around 100 A or better; but on fiber-optic CTs, we can look forward to 10 A level resolution. With such resolution, we will be able to achieve further improvement of reliability of protection systems.
structure with no iron cores (existing Hall effect CTs require some space between each other). The configuration suggests that fiber-optic CTs also enable reduced installation space.

Fig. 8 Prototype Wind Type Fault Selective Equipment

Fig. 9 CT Installed at Nipponi Substation

5 Conclusion

We completed development of a new DC fiber-optic current sensor and accomplished development of practical fault selective equipment using that sensor. Fiber-optic CTs are resistant to affects of adjacent circuit current and enable accurate measurement. And at the same time, they save space and enable easier installation at substations because their small and lightweight structure places few limitations on installation space.

We plan to proceed with development of practical fiber-optic CTs for protection devices in addition to applying them as current measurement sensors.

References: