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APPLICATION OF OPTICAL FIBER CURRENT SENSORS TO UNDERGROUND CABLES

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ABSTRACT

Optical fiber current sensors based on the Faraday effect were expected for a long time as compact and high performance current sensors in place of conventional current transformers. However, widespread practical application of them has not been realized yet, because of complex means necessary for securing stable characteristics. Tokyo Electric Power Company solved the problem, with use of a special fiber as the sensing element, and by constructing sensing system matching with properties of the sensor fiber. The developed sensors are immune from outer environment such as electromagnetic noise, vibration, and temperature changes. Also the sensors are capable of high-speed response and of long distance signal transmission. Furthermore, the sensor head of the devices are compact and flexible. Therefore, by using the developed sensors, current can be detected easily and stably by only encircling the sensor fibre around the current conductors, such as existing power cables.

Taking notice of these strong points, the authors developed a fault section locating system for underground power cable lines applying the sensors, and also developed a fault point locating system using the sensors. The developed systems are applied practically. In this paper, the optical fiber current sensor is introduced firstly. Then the paper describes the fault section locating system and its practical application to a 66kV cable line, and also describes the fault point locating system and practical application of it to a 275kV line.

KEYWORDS

Faraday effect, optical fiber, current, sensor, fault location, cable

INTRODUCTION

Current monitoring is a basic and important technology for the control, protection, and supervision in most facilities sustaining industry and community, such as power facility. Traditionally, the current transformers consist of iron cores and windings have been used for the measurement. However, the followings are recognized as problems of them.

a. Current transformers are heavy and bulky.
b. It is difficult to install them to thick and/or high voltage conductors, and also difficult to attach them to existing apparatus.
c. The measurement signals are influenced by electromagnetic induction noise.
d. Measurement of large current, especially including low frequency component, is difficult.

As a hopeful solution for the problems, in the 1960s, the optical current sensor based on the Faraday effect was proposed **(1).** After that, in the 1980s, a method using optical fiber as the Faraday sensor element (optical fiber current sensor) is proposed **(2).** Then, research and development of the method has been carried out at many institutes for a long time. However, widespread practical application of the sensors has not been realized yet, because of the complex means necessary for securing stable characteristics of the sensors. One of the serious problems was that the polarization of light in the fiber used as the sensing element is affected by mechanical stress in it through the photo-elastic effect.

Tokyo Electric Power Company (TEPCO) developed a novel optical fiber current sensor in which such problems are solved. The developed sensor indicates excellent features such as easiness of stable current detection by only encircling the light and flexible sensor fiber around the current conductor. Taking notice of such features of the sensors, the authors developed a fault section locating system, and also developed a fault point locating system for underground power transmission cable lines, using the sensors.

This paper reports the result. Firstly, sensor technologies are expressed concerning principle, key technologies for securing characteristics, design of a sensor applying the key technologies, and characteristics of that. Then, the fault section locating system is described. Practical application of it to a 66kV line is also reported. Finally, the fault point locating system and practical application of it to a 275kV line is described.

2. OPTICAL FIBER CURRENT SENSOR

2.1 Principle of Operation

When a light beam passes through a transparent medium in a magnetic field, polarization of the light is rotated in proportion to the field. This effect is called "Faraday effect", and is the basic principle of the optical fiber current sensors. The rotation angle is indicated by the following equation,

$$\theta_F = VHL \qquad [1]$$

where,

H: strength of the magnetic field A/m
L: length of the Faraday sensor m
V: Verdet constant deg/A

As indicated in equation [1], the Faraday rotation angle is proportional to the magnetic field. Therefore, by measuring the rotation angle, the value of current to be measured can be known.

Figure 2.1 shows the schematic configuration of an optical fiber current sensor. Light from the source is transmitted to the optical box with a transmission fiber, and linearly polarized light is produced with a polarizer in it, and the light launches into the sensing fiber. In the fiber, Faraday effect occurs by application of magnetic field induced around the current to be measured. Then, light passing through the fiber is inserted into an analyzer in the optical box, and is sprit into two beams whose directions of polarization are orthogonal each other. In this scheme, intensity of the two light beams is changed responding to the Faraday rotation. To obtain good linearity between the light intensity modulation and the Faraday rotation, 45degree difference is set between the azimuth angles of the polarizer and the analyzer (45deg. optical bias). Then, the two modulated light beams from the analyzer are sent to the electronic circuit with receiving fibers, and converted to electrical signals by photo detectors. Finally, by a signal processing circuit, output signal proportional to the current is produced.

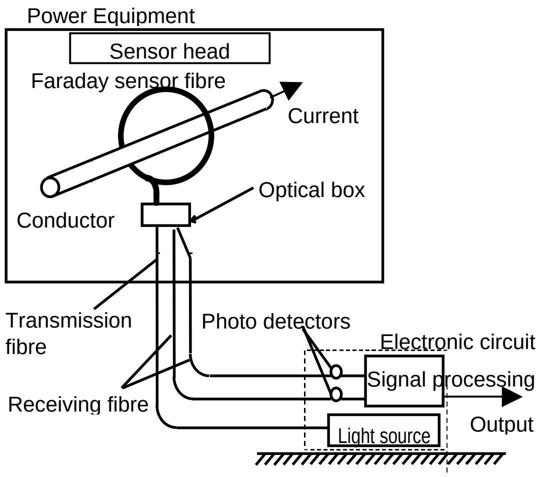


Fig.2.1 Configuration of an optical fiber current sensor

2.2 Key Technologies

Through researches on optical fiber current sensors conducted by many institutes, it has been considered that there are important subjects for the development such as "Stability of the features", "Simplification of the structures", "Reduction of cost". In the development described here, the problems are solved with following methods.

(1) Optical Fiber for the Sensing Element

When optical fiber made from fused silica, for the communication, is used as the Faraday sensor element, polarization of light may be affected by stress due to the photo-elastic effect in the fiber. If this phenomenon occurs, it becomes very difficult to distinguish between the change of polarization caused by the Faraday effect and that of the photo-elastic effect. To solve this problem, various methods were proposed **(2)**.

Table 1.1 Comparison of photo-elastic constants and Verdet constants between flint glass and fused silica.

	Photo-elastic constant	Verdet constant
Flint glass for the sensor fibre	$0.45 \times 10^{-9} cm^2/kg$	8.5×10^{-4}deg/A (850nm)
Fused silica	$350 \times 10^{-9} cm^2/kg$	1.4×10^{-4}deg/A (850nm)

TEPCO developed a special optical fiber made from flint glass of very small photo-elastic constant (Flint glass fiber) in cooperation with HOYA Corporation **(3)**, and is applying it as the sensing element. **Table 1.1** shows comparison on the photo-elastic constant and the Verdet constant between the glass used for the flint glass fiber and the fused silica. From the table, it becomes known that the photo-elastic constant of the flint glass is 1/770 of that of the fused silica. Farther, Verdet constant of the flint glass is about 6 times greater than that of fused silica. Therefore, flint glass fiber is suitable for the Faraday sensor elements due to both the low sensitivity to photo-elastic effect and the high sensitivity of the Faraday effect. Suitable wavelength bands for the flint glass fiber are 1550nm, 850nm and 630nm. In case of 1550nm, the Verdet constant is 0.23deg/kA (45deg/200kA), and the transmission loss is less than 1.3dB/m.

(2) Elimination of Rotation of Polarization Plane Caused by Geometric Effect

There was another problem concerning the polarization of light. That is a phenomenon that the polarization of light rotates depending on shape of curve of the sensing fiber **(4)**, and signal output changes with changes of the curve. This was solved with following measures.

Figure 2.2 shows the phenomenon. As shown in the figure, it is assumed that a single mode fiber with no birefringence makes a 3 dimensional curve, and linearly polarized light is inserted into the fiber at s=0. In this occasion, direction of the polarization plane of the emitted light from the fiber at s=L rotates. It is known that the rotation angle ϕ is represented by the line integration of torsional rate τ along the curve, as represented in the following equation.

$$\phi = \int_0^L \tau(s)\,ds \qquad [2]$$

where,
ϕ : rotation of polarization plane rad
τ(s) : torsional rate of the curve rad/m

If this phenomenon occurs, it becomes very difficult again to distinguish the rotation of polarization plane caused by the Faraday effect from that of the geometric phenomenon. In order to solve this problem, a method of attaching a mirror at an end of the sensor fiber, for making round trip light transmission in it. By the round trip light transmission, the rotation of polarization plane of equation [2] is canceled **(3)**.

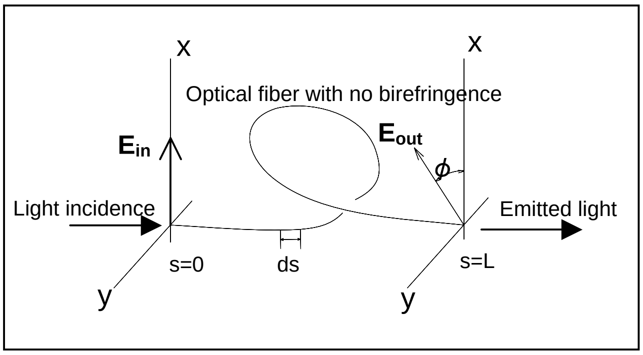


Fig.2.2 Rotation of polarization plane by the geometric effect in a single mode fiber with no birefringence.

(3) Other Means Developed

A signal processing method named "averaging of modulations" was developed **(5)**. By applying the method, effects are obtained on stability of output signal and noise reduction. Further, various methods for establishing high accuracy and reliability were studied. For example, a broad band light source with high spatial coherence is used to suppress the noise caused by interference of light and also to obtain a sufficient receiving light intensity.

2.3 Device Applying the Key Technologies

Figure 2.3 shows a configuration of the sensing device manufactured with application of the key technologies described above.

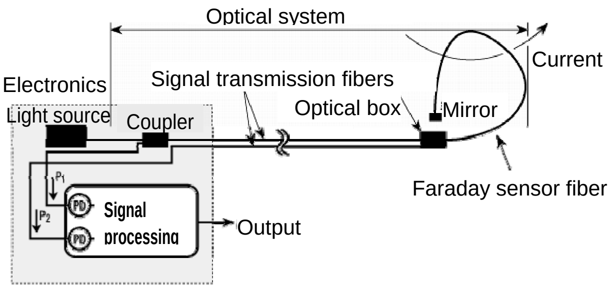


Fig.2.3 Configuration of a Sensing Device

As shown in the figure, the device is composed of a sensor head **(6)**, signal transmission fibers, and electronics. In the electronics, light source, signal processing circuit, driving power source, and others are combined in a package compactly. From the light source (wavelength 1550nm) in the electronics, light is sent to the sensor fiber through a signal transmission fiber and the optical box. The light inserted into the sensor fiber is reflected back from the mirror to the optical box. By the optical bias mechanism in the optical box, the light is divided into two beams and inserted into the two signal transmission fibers, and sent to the electronic circuit. And, intensities of the two light beams are modulated according to the Faraday effect in the sensing fiber. The electrical signals from the photo-detectors are put into the signal processing circuit, and finally, output signal voltage proportional to the current is obtained.

2.4 Strong Points of the Novel Sensor

Before stating on applications of the developed optical fiber current sensor, strong points of the sensor in comparison with conventional current transformers are summarized as follows.

a. Compact and Light: They can be designed as compact because the sensing element is thin, flexible optical fiber, and is insulating material.

b. Easiness of Installation: Installation to existing electric apparatus is easy because the sensor can be equipped without opening the primary power circuit.

c. Immunity from Electromagnetic Noise: They are immune to electromagnetic noise because all parts except for the electronic circuit consist of optical components.

d. Wide Measurement Range: Measurement of high frequency current is possible, and large current with DC component can be detected because they do not suffer the magnetic saturation.

e. Long distance Signal Transmission: Long distance signal transmission is possible because waveform distortion and transmission loss are small.

3. FAULT SECTION LOCATING SYSTEM

3.1 Purpose of the System

In a power transmission system in which underground cable lines are intermingled with overhead lines, fault section locating systems are necessary to detect a fault in the cable section, and to make output signal to the protection relays to lock the reclosing operation of circuit breakers. For this purpose, a fault section locating system using the novel optical fiber current sensors was developed, by a joint work among TEPCO, Takaoka Electric MFG. Co., LTD., and Kansai Electric Power Company **(7)**.

3.2 System Design

Figure 3.1 shows the system configuration. At both ends (A and B) of the underground cable, optical fiber current sensors are installed to the cable, and is capable of detect the zero phase fault current. The signal light from the sensor head whose intensity is modulated by fault current is transmitted, by the signal transmission fibers, to the detection panel set at a substation. At the detection panel, fault current is measured with the O/E conversion board, and the detected value is output to the current differential relay. Then, the relay decides that the fault is in the cable section or outside of that. Finally, when the fault is in the cable section, the relay makes an output signal for locking the reclosing operation.

Two different types of the system were developed corresponding to applicable cable lines. One is for application to 154kV and 66kV lines of resistance grounded neutral systems. Another is for 275kV cable lines of solidly grounded neutral system. One of the reasons that two types were developed is that value of the fault current depends greatly on the neutral grounding systems. Another reason is that structure of installation of the cables around cable heads is greatly different by rated voltages. **Figure 3.2** shows the sensor head and its structure of installation to the cable. The fiber sensor head is attached under the cable head, enclosing around all the 3 phases of the cables. Therefore, accurate zero phase fault current detection (sum of the current of 3 phases) is possible by the sensor with simple structure. This sensor head has water proof structure and it can be set even underground.

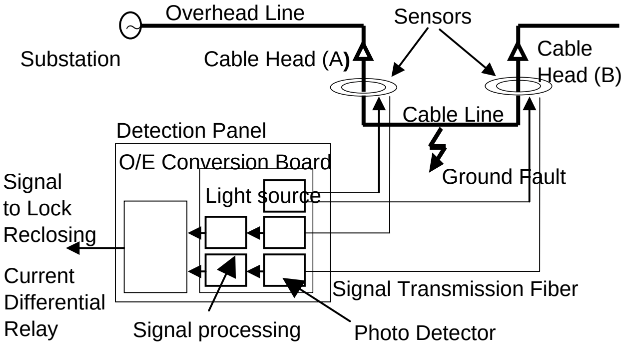


Fig. 3.1 Configuration of the fault section locating system

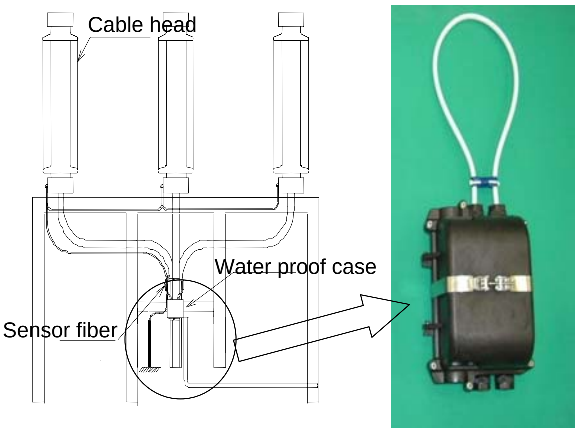


Fig. 3.2 Structure of sensor installation to the cable

3.3 Characteristics

Table 3.2 shows specifications of the optical fiber current sensor.

Table 3.2 Specifications of the optical fiber sensor

Applicable lines		Resistance grounded neutral system 66kV 154kV
Measurement value		Zero phase current
Frequency		50Hz 60Hz
Measurement range		40A ～ 2000A
Ratio-error	Current 40A	less ±4.0%
	Current 2kA	less ±2.0%
Distance of signal transmission		Max. 20km (round trip 40km)

3.4 Practical application

Until now, for the purpose of the fault section location, a system in which fault current is detected by winding type current transformers and signals are sent with metal pilot wire cables has been applied mainly. Merits of the develop system in comparison with the conventional system are as follows.

@ No electronics and no power source are necessary at the portion where the sensors are installed.
@ Longest signal transmission distance is 20km, and application to long distance power line is possible.
@ Attaching the sensors to existing power cables is easy using the reflection type flexible sensors.
@ There is no worry about unwanted operations caused by the magnetic saturation of the iron cores of current transformers in case when a fault occurs outside the cable section with large fault current flows.
@ The sensor head is water proof against submerging.

Taking notice of these strong points, the developed systems are applied practically. Since 2004, Kansai Electric Power Company has applied, and 6 systems are in operation now. And also, in April 2007, TEPCO has started first practical application of this system to a 66kV line with branches. **Figure 3.3** shows the sensors attached to 66kV cables.

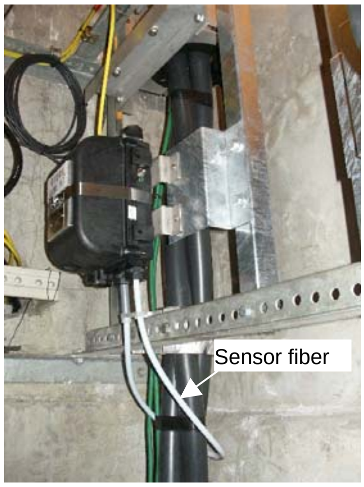


Fig.3.3 Practical application of the sensor to 66kV line

4. FAULT POINT LOCATING SYSTEM

4.1 Purpose of the System

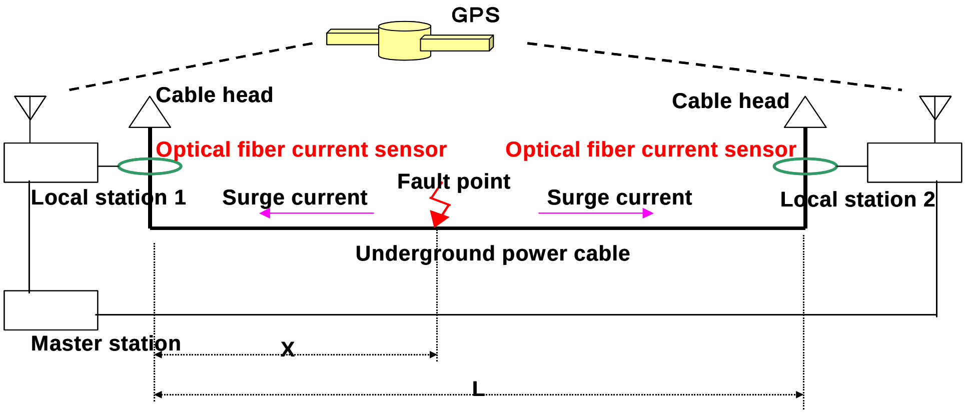
In TEPCO power systems, for the prompt recovery from faults, surge receiving type fault location systems are applied in underground cable lines of rated voltage over 275kV. To secure operation reliability of the systems and other purposes, a fault point location system using the optical fiber current sensors for the surge current detection was developed by a joint research among TEPCO, Toko Electric Corporation, and Fujikura LTD.

4.2 System Design

Figure 4.1 shows a configuration of whole system. The system consists of two sets of optical fiber sensors, two local stations, and signal transmission lines among them. The optical fiber current sensors are attached to power cables below the cable heads.

Operation of the system is as follows. When a fault occurs, each of the optical fiber current sensors detects the surge current that arrives from the fault point, and transmits the signal to the local station. Then, each of the local stations measures arrival time of the surge current precisely with GPS clock, and sent the data to the master station. The master station decides the fault point from difference of the arrival time data sent from the local stations. The velocity of surges is nearly 50% - 60% of speed of light in the space.

Figure 4.2 shows a schematic configuration of a set of the optical fiber current sensors, and **Table 4.1** indicates an outline of the specification of that. As shown in **Fig.4.2**, the device is composed of three sensor fibers for attachment to the three phases of power cables, an optical connection box set near the cable heads, a signal transmission fiber cable, and the electronics. The optical connection box has, in it, an optical fiber coupler to divide light from the source to three sensor fibers, and optical circulators to pick up the modulated light from the sensors in it.



X=(L-VT)/2

V: Velocity of surge, T: Arrival time difference between two surges

Fig.4.1 Fault point locating system for underground cable lines

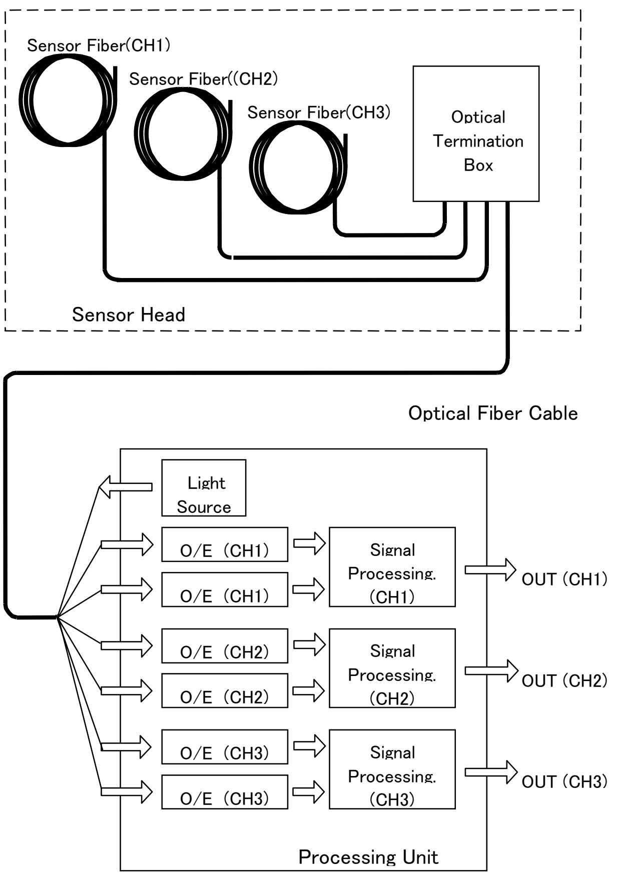


Fig. 4.2 Configuration of the optical fiber current sensors

Table 4.1 Specification of an optical fiber current sensor for the fault point locator

Item	Specification
Number of channels	3 channels
Usage environment	Sensor ：outdoors, electronics ：indoors
Current measurement range	AC100A ～ 2kA （peak value） accuracy：less ±5％
Frequency response	50Hz～250kHz （flat）
Response time	Raise time：under 1 micro sec
Power source	AC100V, frequency：50Hz

4.3 Field Tests

Fault point location test of the developed system applying the optical fiber sensors was done using an underground cable line of TEPCO. Constitution and method of the test was as follows. The optical fiber current sensors were set and connected to local stations at two substations, substation A and substation B, which are located at both ends of the power cable line. The line used for the test is 15.6km length, rated voltage 275kV, Oil Filled cable. After that, to simulate a fault, under the condition that both circuit breakers were open, the circuit breaker of A substation was closed, and switching surge was made. Then, the output signals of the optical current sensors at both substations were observed, and also operation of location of the position where the surge generated was done with the fault point locating system. Same tests were repeated several times.

Figure 4.3 shows a surge current observed at substation A. The rise time of the waveform is 1.3 micro second and peak value of it is over 2720A (the waveform is saturated by the signal processing circuit). Also, figure 4.4 shows the surge current observed at substation B for the same time of the test. The rise time of this wave is 14 micro second and peak value of the that is 37A (time : nearly 200 micro second). The reason of low peak value observed at substation B is mainly caused by reflection wave of surge current generated from the open end of the cable. And also, long rise time of this wave is due to distortion caused by long distance transmission of the surge from substation A. From the results of five times of the test, maximum value of the absolute location error is 48m, and average of the absolute values of the errors is 38m. These values are sufficiently small than the value requested by the specification.

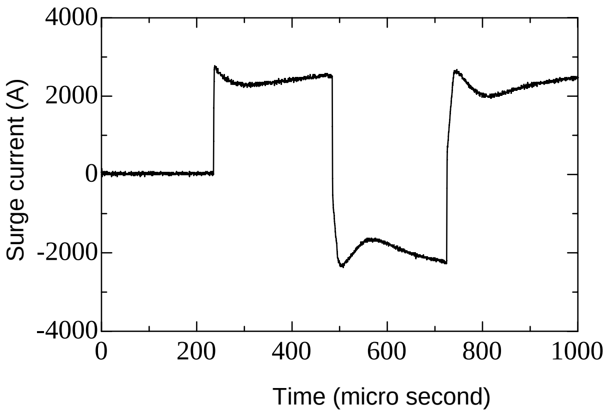


Fig.4.3 A surge current observed at substation A.

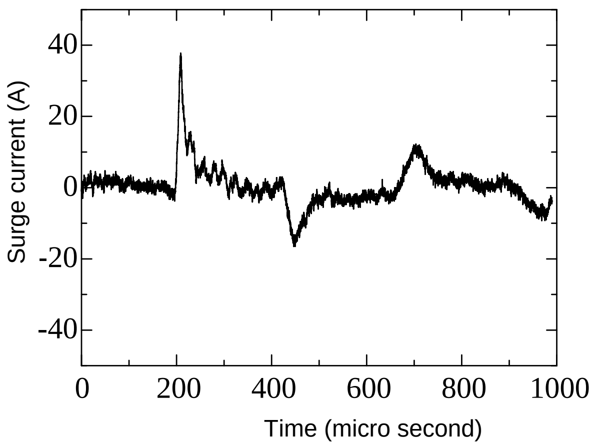


Fig.4.4 surge current observed at substation B

4.4 Practical application

From the field tests using a cable line of real operation, the practicality of the system has been confirmed. By applying these results of the development, a new system for the practical use was designed and manufactured, and it has been applied to a 275kV OF cable line, length 13.9km, in TEPCO facility since March 2007. Figure 4.5 shows a sensor fiber of practical use attached to the cable.

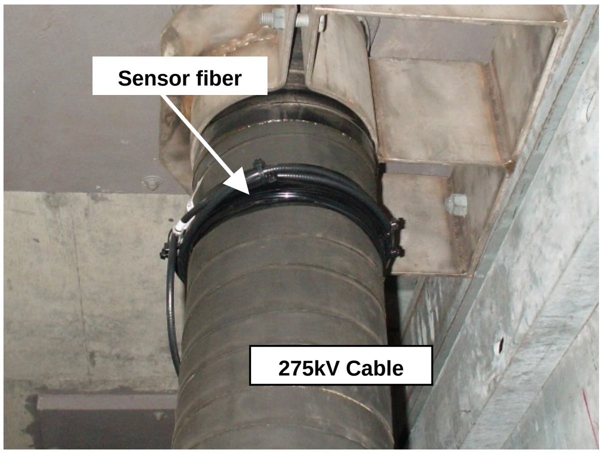


Fig.4.5 Sensor fiber for practical use attached to a cable

5. CONCLUSION

This paper described development of a novel optical fiber current sensor, and also development of a fault section locating system and a fault point locating system using the sensors. Practical applications of the developed systems are also reported. By using the new sensor devices, stable detection of current is possible by only encircling the sensor fiber around the cable. The new sensor also has other strong points such as immunity from electromagnetic noise, capable of long distance signal transmission, fast response, ease of electric insulation. As described in this paper, such strong points are utilized in the new systems for fault section location and fault point location applied in the underground power lines.

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