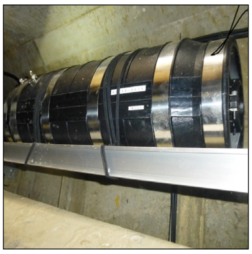

Manhole Monitoring System Using Existing Power Cables as Transmission Line

Tetsuo GOTO*, Tai YOKOYAMA, Takefumi SHIMOGUCHI,
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In the maintenance of underground transmission lines, there is a need to shift from time-based maintenance, where maintenance is performed manually and periodically, to more advanced condition-based maintenance, where maintenance is performed efficiently when necessary, through the promotion of digital transformation using IoT and AI to achieve smart maintenance. One of the challenges in realizing IoT has been the difficulty in developing an inexpensive, safe, and reliable communication method to acquire sensor information about cables installed in conduits, which account for the majority of underground power transmission facilities. This paper describes the development of a system that collects sensor information and camera images using a 66-kV XLPE cable installed in a conduit manhole, in collaboration with TEPCO Power Grid, Inc.

Keywords: manhole, underground transmission lines, power line communication, transmission through shielding layer, maintenance monitoring system

1. Introduction

Conventional inspection and maintenance of underground power transmission lines are mainly based on time-based maintenance (TBM) consisting of periodic patrols (appearance inspection) of cables and incidental facilities, combined with manual measurement of oil leakage, cable displacement, temperature changes on the cable surface, and partial discharge, and analysis of gas. In recent years, however, problems such as aging of transmission lines and a future shortage of maintenance personnel have become tangible, and there is a strong need for promoting smart security. Under such circumstances, it is desired to sophisticate condition-based maintenance (CBM) by promoting the use of digital transformation (DX) using the IoT, sensor technology, artificial intelligence (AI), and other advanced technologies.

Underground transmission lines are installed in underground tunnels and conduits. In order to realize the IoT, it is necessary to create a low-cost, high-reliability, and high information security sensor network that can transmit various kinds of sensor data necessary for maintenance from a point underground. In particular, the manhole sections of a conduit have posed the following issues:

(1) If there is no empty conduit provided for the existing transmission line, it is difficult to newly install metal or optical fiber communication lines. Even if an empty conduit has already been installed, it is costly to install communication lines in the conduit.

(2) When wirelessly transmitting sensor data from a manhole, it is costly to construct a data collection network due to a short radio wave reaching distance.

(3) It is difficult to secure a power supply for the sensor and data transmitter.

(4) The sensor and data transmitter are required to be highly water resistant because the manhole is often submerged.

A system for wirelessly measuring the displacement of power cables(1) and a maintenance monitoring system that uses wireless communication, such as 920 MHz band low power wide area (LPWA), have already been reported.(2) Double metal covers are usually used for manholes in preparation for a transmission line outage. This limits the communication distance to some hundreds of meters due to large attenuation of wireless communication. Furthermore, if the manhole is submerged, the communication distance will further decrease.

To solve these problems, we developed a low-cost, high-reliability, and high-security communication system that can collect data from sensors installed in manholes without installing a new communication line. This system is based on power line communication (PLC) technology and uses the shielding layer of the existing power cable as the transmission path. We have also developed a maintenance monitoring system for transmission lines in manholes by applying the new communication system. This paper outlines the features of the new system.

2. PLC Transmission Using the Shielding Layer of Power Cable

PLC is a communication technology that superposes high-frequency carrier signals on an existing power line. Two types of PLC are used in Japan: kHz-band and MHz-band PLC. For the new maintenance monitoring system, we adopted kHz-band PLC that uses frequencies from 10 to 450 kHz. Due to smaller attenuation compared to MHz-band PLC, kHz-band PLC was expected to allow long-distance transmission while avoiding interference with the frequency band (MHz band), which is useful for diagnosing the deterioration of power cables by partial discharge measurement.

When the conductor of a high-voltage or extra-high-voltage power cable is used as a transmission path, the coupler for superposing the signals must be upsized to withstand the high voltage, and the coupler connection point is limited to the ends of the conductor. A power cable joint box is installed in the manhole, and a bonding wire connecting the shielding layers of the cables, shown in Fig. 1, and a grounding wire are pulled out of the joint box. A current transformer (CT), which enables non-contact inductive coupling of signals to these cables, was used to utilize the shielding layer as a transmission path. Table 1 compares the conductor-based and shielding-layer-based transmission methods.

Photo 1 shows the appearance of the CT to be clamped to a bonding wire or grounding wire. Due to small dimensions (105^{W} × 85^{H} × 120^{D} mm), the CT is easy to install. Using the CT to superpose the carrier signals of PLC on the grounding wire, we conducted communication with a unit of equipment located in another place.

Following the above, we carried out a PLC-based transmission test using the shielding layer of the in-service power cables shown in Fig. 2.

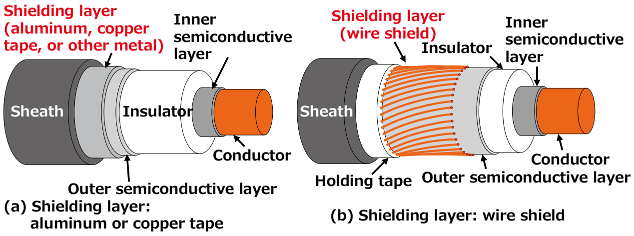


Fig. 1. Structure of power cable

Table 1. Comparison of transmission methods

	Conductor-based transmission	Shielding-layer-based transmission
Signal coupling	Capacitive coupling	Inductive coupling
Signal injection point	Terminal	Terminal or joint box
Transmission distance	Enables long-distance transmission	Enables relay of transmission, though transmission distance is shorter than that of conductor-based transmission
Installation condition	Requires large-size units Imposes severe installation restrictions	Enables the use of small-size CT Imposes mild installation restrictions
Usability	Imposes upper limit of voltage on applicable cable	Does not impose upper limit of voltage on applicable cable
Leakage of electromagnetic field	Free of the effect of leakage of electromagnetic field due to underground burial	
Evaluation	Unsuitable for IoT	Optimal for IoT

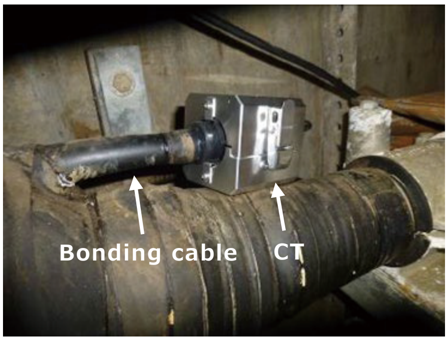
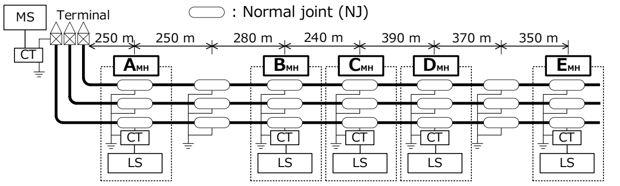


Photo 1. An example of induction coupling of CT to bonding cable or grounding cable



Cable category: XLPE (CV) Voltage class: 66 kV Conductor cross-sectional area: 500 mm^2 Structure of shielding layer: wire shield Grounding method: solid-bonding method
MS: Master station LS: Local station

Fig. 2. Test configuration

Table 2 shows the results of a direct communication test between local stations (LSs) installed in manholes and a master station (MS) connected to the cable terminals, or between individual LSs installed in the manholes.

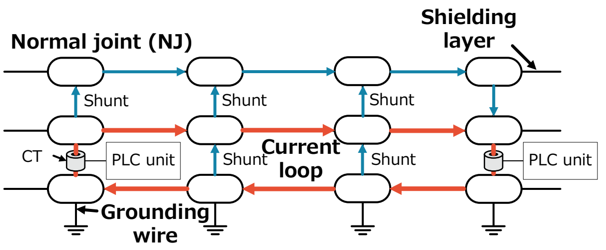
Table 2. Communication test results for 66 kV CV cable

Communication direction	Item	Between MS and LS A	Between MS and LS B	Between LS B and LS C	Between LS C and LS D	Between LS D and LS E
Upstream	Success rate (%)	100	100	100	100	100
	Effective speed (kbps)	20.1	0.9	20.5	19.6	20.3
Downstream	Success rate (%)	100	100	100	100	100
	Effective speed (kbps)	19.8	1.1	20.3	20.1	19.1

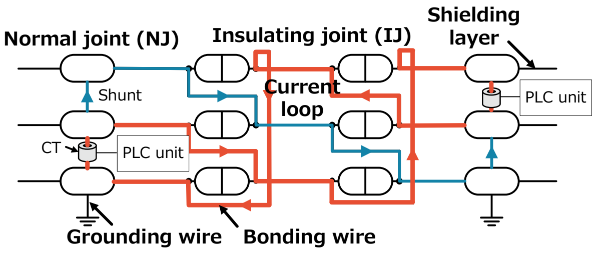
In the test, a packet of 1,232 bytes was transmitted 100 times between individual units to measure the communication success rate and average effective speed.

The communication success rate was 100% in both the upstream and downstream directions. The effective speed decreased between the MS and LS B as shown in Table 2. As shown in Fig. 3, signals are inductively coupled to the shielding layer by the CT and form a current loop between adjacent normal joints (NJs) using the shielding layer of the other phase. As a result, the signals are transmitted. Signals were attenuated more significantly when passing through the NJ due to shunt than when transmitted through the shielding layer. The probable reason for the decrease in effective speed between the base unit and LS B is that signals were attenuated significantly when passing through NJs in three sections and caused the signal-to-noise-ratio to decrease.

In this paper, the solid bonding method is discussed as an example. However, when the above two grounding methods are viewed in terms of grounding section in signal propagation, there is no significant difference between the cross bonding method and solid bonding method, excepting that the cross bonding method switches the signal propaga-



(a) Solid bonding method



(b) Cross bonding method

Fig. 3. Formation of current loop in each grounding method

tion phase in the insulating joint. Therefore, assuming that the distances between individual joint boxes are equal, the cross bonding method is considered to give a relatively longer transmission distance than the solid bonding method because the distance between NJs for the former method is about three times larger than that for the latter method.

3. Specifications of Maintenance Monitoring System for Transmission Line in Manhole

3-1 Configuration of maintenance monitoring system for transmission line in manhole

PLC-based data transmission through shielding layers enables highly reliable data transmission required for the IoT. Figure 4 shows the configuration of the system for monitoring a transmission line in the manhole using this transmission technology.

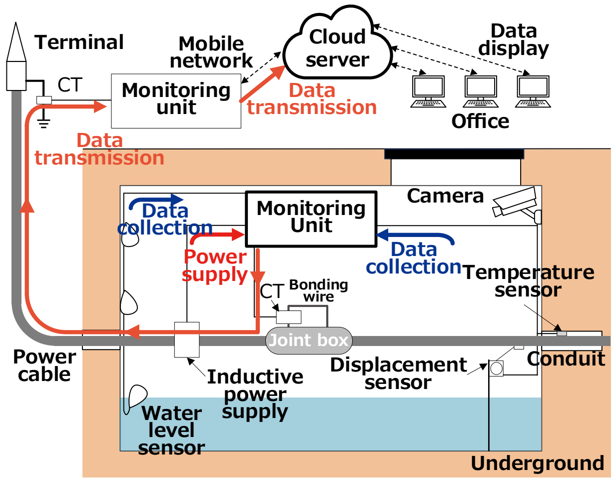


Fig. 4. Configuration of maintenance monitoring system for transmission line in manhole

A transmission line monitoring unit is installed in the manhole. The monitoring unit on the ground makes it possible to connect a maximum of 10 monitoring units in the manholes by the PLC technology. Each monitoring unit acquires sensor information. The unit uses the PLC transmission technology to transmit the sensor information through the shielding layer of the transmission line to an outdoor cable terminal that enables the use of mobile networks and other general-purpose communication means. Then the data are transmitted to a cloud server through a mobile network. The cloud server stores the data to enable offices and other workplaces to check them as monitoring data.

3-2 Items to be monitored in manhole and sensors used

This paper discusses the monitoring of a transmission line in a manhole. The monitoring items and sensors used for the monitoring are shown in Table 3. General-purpose sensors and cameras were used for the monitoring in consideration of cost and labor savings. Manholes located in lowland areas are partially submerged due to the inflow of rainwater or groundwater. With such situations in mind, units and sensors that would work even if they were submerged to a depth of 10 m were used. The imaging camera was also protected from water with a specially developed housing (Photo 2).

Table 3. Items and sensors used for monitoring the interior of manhole

Monitoring object	Measurement item	Sensor used	
		Sensing method	I/F
Internal state	State	Camera	USB
Cable displacement	Displacement	Potentiometer	AI
		Camera	USB
Water level inside manhole	Water level	Float-type sensor	DI
		Camera	USB
Surface of cable and interior of conduit	Temperature	Resistance temperature detector	AI

AI: analog signal DI: contact signal

Photo 2. Example of camera installation in manhole

3-3 Specifications of monitoring unit for transmission line in manhole

Table 4 shows the main specifications of the monitoring unit for the transmission line in the manhole. Since general-purpose sensors are used to monitor the transmission line installed in the manhole, signal converters are additionally needed. There are two types of outputs from general-purpose sensors. One is analog signals generated from the temperature sensor and displacement sensor, while the other is contact signals generated from the float-type water level sensor. In the case of analog signals, the amounts measured by the sensors are output after being converted to currents of 4 – 20 mA by the signal converters. Contact signals are generated by turning contacts on and off. We developed a sensor output converter to further convert these signals into PLC signals.

To protect the transmission line monitoring unit installed in the manhole, we used a housing that enables the unit to continue working even when it is submerged to a depth of 10 m. This housing has been proven to be effective for connecting underground optical cables (Photo 3).

An inductive power supply unit, which generates electricity from the current in the power cable using electromagnetic induction, was used to supply power to the monitoring unit located in the manhole.

Table 4. Main specifications of monitoring unit for transmission line in

Item		Specification
I/F	Analog signal (AI)	4 ch
	Contact signal (DI)	3 ch/contact (input)
	USB	2 ports
Power supply/power consumption		12 VDC/18 W or less
Dimensions		W272 × H272 × D673 mm (Excepting protrusions)
Weight		Approx. 15 kg
Place of installation		Inside manhole (IP68, Max. water depth: 10 m)

Photo 3. Monitoring unit for transmission line in manhole

4. Application to Maintenance Monitoring System for Transmission Line in Manhole

4-1 Image-based monitoring of transmission line in manhole

Traditionally, it has been extremely rare to continuously monitor the inside of manholes by means of images due to difficulty in data transmission and power supply. This time, as an example of monitoring, we took images, focusing on the overall view of the inside of a manhole and cable. Since the transmission line in the manhole, including the cables, is rarely displaced significantly, it is possible to detect changes in state by performing differential analysis of the images. Observation of the overall view shown in Photo 4 (a) will enable early detection of abnormalities, such as damage to the transmission line inside the manhole during an earthquake or other disaster and abnormal offset of the cable. Photo 4 (b) shows a cable behavior detection test. In the test, we took a photo of the markings put on a cable at six-hour intervals from a point near the cable and analyzed the images (by binarization and differential processing). The results are shown in Fig. 5.


(a) Overall view of the inside of manhole
(b) Markings put on cable

Photo 4. Overall view of the inside of manhole and cable

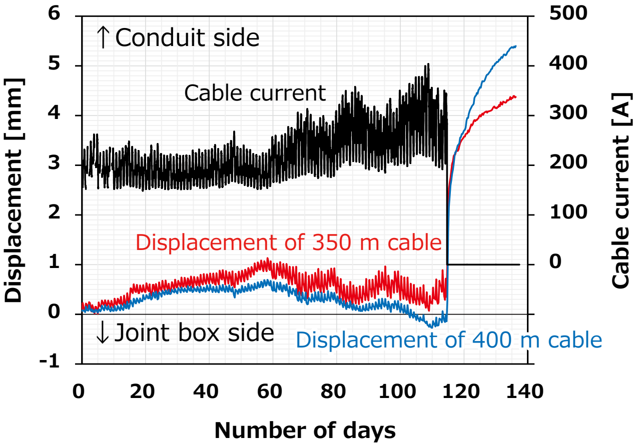


Fig. 5. Changes in cable displacement and cable current

For 137 days after the start of shooting, the current of two cables and their behavior near the conduit openings at both ends of the manhole were monitored. The lengths of these cables monitored in the conduit were 350 m and 400

m. The variation of the cable current during the measurement period fell within the range of roughly 150 A to 400 A, and the small displacement of the cables during the daytime was dependent on the variation of the current during the daytime. In addition, small expansion and contraction of 1 mm or less could be measured during the energization period. The plus direction in the figure represents the contraction of the cables toward the inside of the conduit. Since the variation range of the load current remained almost unchanged for about 60 days from the start of the measurement (September 26), the cables gradually contracted toward the inside of the conduit as the temperature dropped. However, after that, the cables tended to gradually expand since the current increased its variation range. When the line was stopped for maintenance on the 115th day, a drastic shrinkage (3 mm or more) was observed in association with a drop in conductor temperature. Since the cables were 66 kV CVT cables, they were designed without consideration of expansion and contraction attributable to load current. However, it was confirmed that these cables cause minute changes in the order of millimeters. The displacement of the cables was also detected by separately installed displacement sensors.

The water level was also detected by comparing the image shown in Photo 4 (a) with the water gauge that can be seen near the center of the image. As a result, continuous change in water level could be captured in contrast to step-by-step water level detection using three float-type water level sensors.

Monitoring the state inside a manhole by means of images enhances the capability to check the state of transmission lines when compared to monitoring with only sensors. For example, digitization of cable displacement using images makes it possible to use the digitized displacement as sensor data, and it is expected to create higher added value.

4-2 Seasonal variation of ambient temperature around cable in manhole

The allowable current, thermo-mechanical behavior, time-related thermal deterioration, and other properties of cables are affected by the temperature conditions around the cables. The cable ambient temperature data measured this time were used to grasp seasonal environmental changes. The temperature distributions in five manholes shown in Fig. 2 and in the empty cable conduit between C and D were measured for about five months from the end of September. In addition, supplementary data, such as water level in each manhole, were also measured.

Table 5 shows the environmental conditions of each manhole. It was confirmed from the results of water level detection during the measurement period that C, which was deep from the ground, was immediately submerged even after the water was drained. On the other hand, B and D, which were adjacent to C, were exposed to flooding and entry of water inside, although the rate of flooding depended on rainfall and other seasonal factors. In contrast, A and E were not submerged during the measurement period.

Table 5. Environmental conditions of manholes

MH	Height above sea level (m)	Depth below ground (m)	Submergence
A	9.7	3.9	No
B	10.5	3.9	Yes
C	12.3	8.2	Yes
D	15.3	5.8	Yes
E	41.0	6.0	No

The change in differential temperature between the surface temperature of the cable in the manhole and the ambient temperature inside the manhole, as well as the change in load current, in December is shown in Fig. 6. A strong correlation between the differential temperature and load current was found, and the time delay of the temperature change with respect to the load current was about four hours. Since the surface temperature of the cable is affected by the temperature inside the manhole and current, a study was conducted on the seasonal change of temperature inside the five manholes that were used for the measurement.

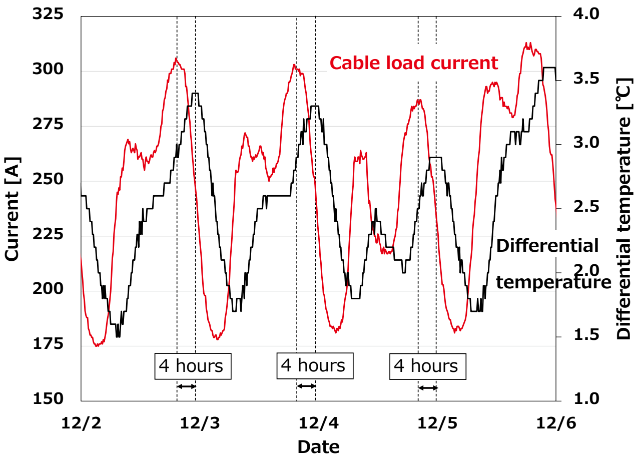


Fig. 6. Change in differential temperature between the surface temperature of cable in manhole and the ambient temperature inside manhole and change in load current

The temperature environment around the cable is considered to change depending on the conditions of each manhole and the properties of the soil in the area where the cable is buried. The ambient temperature inside the manhole was measured. The temperature inside the empty conduit adjacent to the conduit containing the cable used for the measurement was also measured in the conduit section between C and D. Figure 7 shows the maximum temperatures recorded in September and February. To measure the temperature inside the empty conduit, a platinum resistance thermometer sensor was installed at places about 50 m and 100 m inside from the conduit opening in C and about 30 m and 100 m inside from the conduit opening in D. For reference, the detailed measurement positions are indicated by dotted lines in Fig. 8, which shows the temperatures measured by means of fiber thermometers.

It was confirmed from the measurement results for the temperature inside the empty conduit that the conduit temperature reached the highest value in the summer season (September). The measurement results also showed

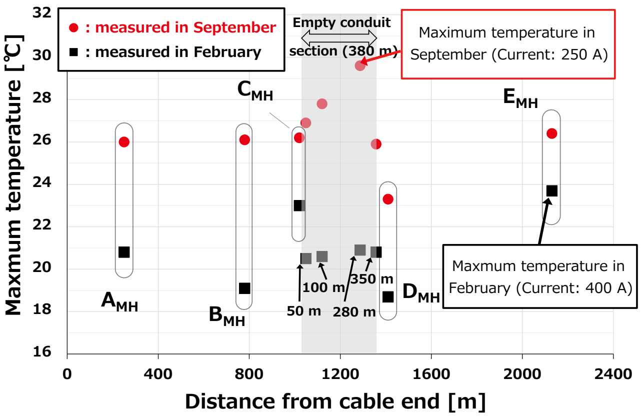


Fig. 7. Ambient temperature inside manhole and temperature inside empty conduit

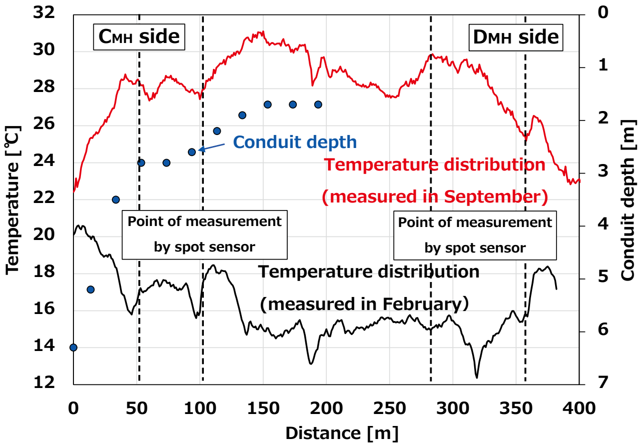


Fig. 8. Temperature distribution inside empty conduit

that, in the winter season, the temperature inside the empty conduit dropped below the temperatures inside some of the manholes. During the winter season in particular, the temperature inside E, which was located on a hill, and the temperature inside C, which was often submerged, were higher than the temperature in the conduit section. The probable reason for the above is that the temperature inside E was increased by the temperature rise inside the manhole, where the heat generated from the cable was continuously dissipated into the air, while the temperature inside C was affected by the temperature of water in which the cable was submerged. For reference, the results of spot measurement of temperature distribution in the empty conduit using a fiber thermometer in the summer and winter seasons are shown in Fig. 8.

The rate of temperature rise in the summer season from the mouth of the conduit towards its center increases as the cable burial depth decreases. This is probably due to the fact that the effect of the outside air temperature on the temperature distribution in the soil increases as the depth under the ground surface decreases. Even in the winter season, the temperature inside the manhole is also affected by the decrease in soil temperature due to a decrease in the outside air temperature. However, the temperature change inside the manhole is less than that in the conduit section, and this fact is considered to have created an opposite trend in temperature change. The temperature distribution inside the conduit in the summer season at a point 50 m or more inside the mouth of the conduit was within a variation range of about ±1°C from 29°C, the temperature at the center (200 m) point. Although measuring the temperature distribution continuously with a fiber thermometer is the best way to grasp the temperature distribution, it is difficult to permanently install a measuring instrument inside the manhole. When measuring the temperature distribution inside the pipeline in a specific manhole section, satisfactory temperature distribution data will be obtained by measuring spot temperatures at short intervals.

In the future, when inquiring into the allowable current of a cable based on dynamic line rating (DLR), it is necessary to consider the temperature conditions around the cable to find a hot spot where the temperature condition is severe, thereby clarifying the effect of the hot spot on the conductor temperature. The following findings were obtained from the results of the measurement that was conducted recently for a long period of time for cables installed in conduits.

(1) It was found from the measurement results for the temperature inside the empty conduit that the temperature around the cable installed in a conduit is significantly affected by seasonal temperature changes. A maximum temperature difference of 16.1°C was observed between September and February at a point with 1.7 m of soil cover (150 m distant from the conduit opening).

(2) Soil temperature in the C-D section is considered to be lower than that in the dry soil environment because of the inflow of groundwater from the surrounding area.

(3) Since the soil moisture content around E is expected to be lower than that in the C-D section, the temperature will rise higher in the area around E than the C-D section in the summer season.

Since the load current during the summer season was smaller than that during the winter season in this measurement, the effect of the temperature rise on the cable was small. Accumulation of data using a section with small soil moisture content, thin soil cover, and large heat generation by the load current (while taking into account the drying of the soil around the transmission line due to heat generated) will be useful for further clarification of the thermal environment around the power cable.

5. Conclusion

We have developed a data transmission technology that uses the shielding layers of power cables as transmission paths and evaluated its characteristics. As a result, it has been verified that a highly reliable IoT network capable of high-security transmission of information even from inside a manhole can be constructed using PLC transmission through the shielding layer of a power cable. Conventionally, it has been difficult to secure a method for transmitting information from a manhole. The data from general-purpose sensors and cameras installed in a manhole are stored on a cloud server as digital information for a long period of time. Analyzing the digital information is useful for the detailed clarification of power cable behavior. This paper presented an example of analysis that captures seasonal changes of the temperature environment around a power cable by means of image-based digitization, which has been attracting attention in recent years as a means of realizing smart security, and combining the digitized temperature and water level data. In the future, this manhole temperature monitoring technology is expected to be used for DLR of the cables to be installed in conduits.

Digitization and accumulation of data on underground transmission lines and the utilization of IoT and other advanced technologies are expected to lead to conversion to CBM and the development of preventive maintenance in the future.

In order to promote DX in the field of operation and maintenance of underground transmission lines, we will introduce a system capable of measuring partial discharges inside manholes using the maintenance monitoring system we have newly developed for transmission lines in manholes. We will also utilize artificial intelligence and other advanced techniques to accumulate data on underground transmission lines and analyze images, thereby promoting the sophistication of the maintenance and operation of underground transmission lines.

Finally, we would like to express our deepest gratitude to all the related staff members of TEPCO Power Grid, Inc. for their support in the development of this maintenance and monitoring system and the implementation of a test using an actual transmission line.

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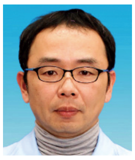

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