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Heating-assisted Current Integration Method as a Tool for Evaluating the Leakage Current in Cable Insulation

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***Abstract*— Cables installed in a boiling-water nuclear power plant were removed from three places. The electrical insulation performance of their flame-retardant ethylene-propylene-diene rubber insulation was examined by the current integration method. Namely, the electric charge stored in a measuring capacitor set in series with the sample cable was measured when a high DC voltage was applied. The ratio of the charge stored in the capacitor in the whole period of voltage application to the initial one was found to be a direct indicator of the leakage resistivity of cable insulation. The resistivity was measured much lower when a part of the cable sample was heated to 80 ℃ than when the whole length was kept at room temperature. This means that the heating-assisted current integration method can be a tool for locating deteriorated positions in the cable insulation. It has also become clear that the cables removed from the three places possess high enough insulation resistivity.**

***Index Terms*— Aging, cable insulation, degradation, gamma-ray effects, insulation testing, leakage current**

I. Introduction

A safe and secure society is realized using equipment that has been type-approved in the whole area so as to be used safely during the specified operating period. In particular, the necessity of type approval is of prime importance for the equipment, the integrity of which is not easy to confirm after it has been installed. Electric cables are one of the typical examples. Therefore, the integrity of cable insulation is dependent on the installation of type-approved cables, even at a nuclear power plant (NPP) where the total length of laid cables exceeds 1,000 km per unit. In other words, it can be said purely logically that the insulation integrity of cables is not guaranteed beyond the type-approved period.

It was around 1970 that a large number of NPPs began operating worldwide. In those days, many NPPs were expected to run for 40 years. Logically, since around 2000, nuclear power regulatory authorities around the world have become more concerned about the aging of cable insulation. For example, the Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD-NEA) set up a committee to deal with this issue [1], and one of the authors of this paper (YO) served as a committee member.

As mentioned in our previous paper [2], among the cables in NPPs, those required to function in the event of an accident or emergency are called safety-related cables. Especially the ones installed in equipment for dealing with severe accidents have the mission of safely terminating an accident when it happens [3]. Cables in NPPs, especially those laid inside a containment vessel, are exposed to temperatures higher than room temperature and radiation, depending on their places. In addition, when an accident occurs, they can be exposed to heat, high-dose-rate radiation, and water steam that may contain chemicals.

Cross-linked polyethylene (XLPE), flame-retardant (FR) XLPE, FR ethylene propylene diene rubber (EPDM), FR cross-linked polyolefin (XLPO), and silicone rubber are used for the insulation of the safety-related cables in Japan. Furthermore, epoxy resin, to which a rubber component is added depending on the reactor type, is used for electrical penetrations that connect cables inside and outside a containment vessel. With this background, large-scale research projects to investigate the changes in insulation properties of the above insulators, either in the shape of a cable removed from an NPP or sheet, due to exposure to heat, radiation, water steam, etc., have been carried out, especially in the United States [4] and European countries [5, 6], as well as in Japan for XLPE [7], FR-XLPE [8, 9], FR-EPDM [2, 10-12], FR-XLPO [13, 14], silicone rubber [15-17], and epoxy resin [18-20].

In this study, cables were harvested from an NPP after being used for a long time, and the leakage current passing through their polymeric insulation induced by the application of DC voltages was measured using the current integration method. To the authors' best knowledge, very few peer-reviewed academic papers have measured the leakage currents passing

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through the insulation of cables removed from actual NPPs and reported on the effect of aging on its conductivity [2]. In conducting measurements, we paid attention to the effect of heating a part of the cable to 80 °C on the adequacy and sensitivity of the measurement method.

II. Samples And Experimental Methods

A. Samples

The samples used for the experiment are three cables harvested from the reactor containment vessel at Unit 6 of the Tokyo Electric Power Company's Kashiwazaki-Kariwa NPP. Its reactor is of an advanced boiling light-water type and started its commercial operation in November 1996. All three cables, called FR-PN cables, are for low voltages with a structure shown in Fig. 1, which also shows the voltage application method. The number of cores is five, each colored black, white, red, green, and yellow. Each core has an FR-EPDM insulator of 0.8 mm thick and a conductor consisting of seven stranded wires with a diameter of 0.6 mm. The nominal cross-sectional area of the conductor is 2 mm^2. The cable has a FR chloroprene rubber sheath of 1.5 mm thick with a finished outer diameter of 13 mm. The insulation contains necessary additives and pigments. The length of each cable is 2.0 m.

Table 1 shows the names of the three cables used in this paper. It also lists the temperatures, irradiation dose rates, and atmospheres of the environments [21] and the periods in which they were placed [22]. The first three letters KK6 are the abbreviation of Kashiwazaki-Kariwa NPP Unit 6, while the fourth letter E represents EPDM. The fifth letter represents the high temperature/high dose by A and the high temperature/low dose by B, while C represents the low temperature/low dose. In 'Temp.', we considered the temperature rise due to cable current and margin [21]. The 'Period' describes the actual operation period of the reactor until cable removal, excluding the periods of periodic inspection and the shutdown due to the 'Fukushima accident' that occurred in March 2011 [22]. Furthermore, since KK6 is a boiling water reactor, the atmosphere inside its containment vessel is nitrogen, close to the atmospheric pressure.

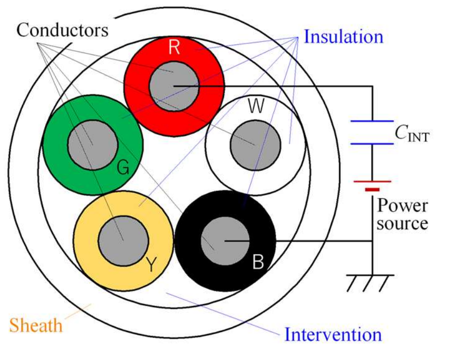

Fig. 1. Cross-section of cable samples (not to scale) and the voltage application method. B, W, R, G, and Y indicate the colors of the insulation. C_{INT}: Refer to Fig. 2.

TABLE I
Environmental conditions around the three cables removed from Kashiwazaki-Kariwa Unit 6.

Sample	Temp. °C	Radiation Dose Rate mGy/h	Period years*	Atmosphere
KK6EA	50.3	17.2	11.3	Nitrogen
KK6EB	50.5	1.1	11.3	Nitrogen
KK6EC	42.3	1.1	11.3	Nitrogen

* Estimated operating period excluding those suspended

B. Experimental Methods

As in the case of our previous paper [2], we used the current integration method to measure the leakage current flowing through the cable insulation. Despite this method being based on a straightforward and well-known principle, it is an innovative and reliable tool for measuring leakage current passing through an insulating material regardless of its shape [23, 24]. Its schematic diagram is shown in Fig. 2. At the time of measurements, the measuring instrument consisting of a measuring capacitor and a transmitter was placed between the cable sample and the high-voltage power supply to eliminate the effects of stray capacitance. Here, R_P is a resistor of 2 MΩ to protect the charging resistor and measuring instrument.

As shown in Fig. 1, we apply a positive DC voltage between the conductors of the red and black cores while the remaining white, yellow, and green ones are electrically floated. Since no conductors are connected, electric current mainly flows through the FR-EPDM insulation of the two cores and the intervention. The flowing electric current is to be stored in the form of electric charge Q in a measuring capacitor set in series with the sample, as we mentioned the details of the method elsewhere [23, 24]. The end of the cable not connected to the measuring device was wrapped with an insulating tape to prevent creeping discharge.

The DC voltage was applied between the red and black conductors, as shown in Fig. 3, in cycles, each consisting of a voltage application time of 180 s and a short-circuited time of 60 s. It was raised stepwise by 0.2 kV in a relatively low voltage range up to 2 kV and by 2 kV in the higher range. After the end of one cycle, the sample was not changed, and the measurement

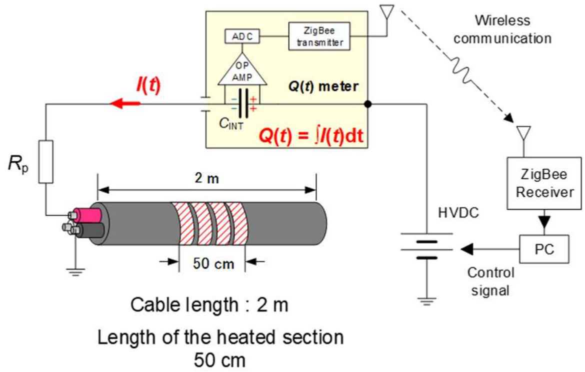

Fig. 2. Schematic diagram showing the principle of the current integration method to measure the leakage current of a sample.

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was continued under the one-step higher voltage. However, if the value of Q exceeded the measurable range during voltage application, or creeping discharge occurred, the measurement was terminated at that point to protect the measuring equipment.

As a function of the voltage application time t, the charge amount $Q(t)$ was measured at intervals of 2 s. When the voltage is applied, $Q(t)$ increases rapidly because of the flow of a high capacitive current. Approximately 2 s after the start of voltage application, the charging of the capacitor is almost completed, and the slope of $Q(t)$ decreases sharply. This amount of Q is called Q_0. Then the current flowing through the cable insulation becomes negligibly low, composed only of the leakage current. The value of Q stored at the end of each voltage application divided by the initial amount Q_0, $Q(180)/Q_0$, can be an index of the leakage current. Namely, if almost no leakage currents flow through the sample, $Q(180)/Q_0$ holds low values near 1.0.

Since we measured $Q(t)$ every 2 s, setting $Q(2)$ measured at 2 s as Q_0 does not have a rigorous scientific meaning. However, $Q(180)/Q_0$ can be a sufficient index of the leakage current for our purposes. The ratio of $Q(180)/Q_0$ is hereinafter referred to as the charge ratio. The superiority of this method is that a minute leakage current flowing in a sample can be calculated, which is not easy with a conventional ammeter, regardless of the sample shape.

Experiments were performed at room temperature (approximately 25 °C) or while the sample cable was partially heated to 80 °C. In the case of partial heating, a ribbon heater was wound around a portion of 50 cm of the cable with a total length of 2.0 m, as shown in Fig. 4. A temperature controller (Hakko Denki, DG2N) was used, and the temperature was measured by a thermocouple inserted between the heater and the cable.

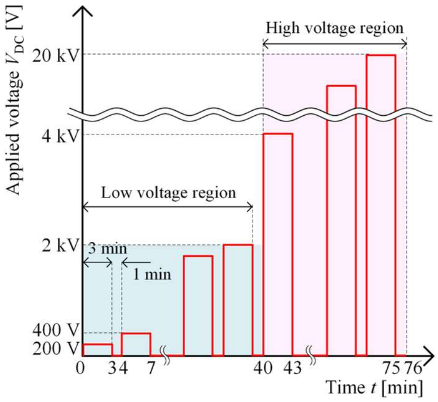

Fig. 3. Example of the stepwise voltage application method for raising the DC voltage. The voltage is increased stepwise by 0.2 kV in the low voltage region and by 2 kV in the high voltage region.

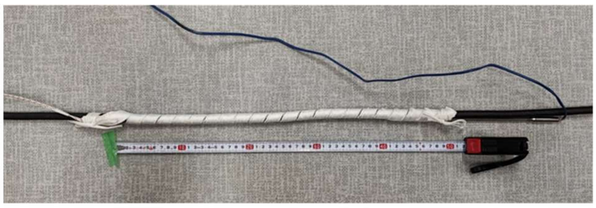

Fig. 4. Photo showing the partial heating method by wrapping a ribbon heater.

The partial heating method was also adopted in a previous paper [25]. The reason for the heating is that the leakage current in polymeric insulating materials, in general, becomes higher with an increase in temperature, allowing the expectation of higher measurement sensitivity. This also makes it possible to perform the measurements under the application of a low voltage to avoid adverse effects on the sample due to the application of a high voltage. The reason for the heating locally is that when a cable degrades locally, a large leakage current flows only when the degraded part is heated. This brings about the possibility of locating the degraded part by this method. Assuming that this method is applied to the fault location of a cable actually in operation, a large-scale heating device is required to heat the entire cable, but a simple heater is sufficient for heating a portion of the cable.

III. Experimental Results

A. Cable KK6EA

First, we pay attention to the results acquired for cable KK6EA, which was installed in the high-temperature and high-dose environment among the three cables. Fig. 5 shows $Q(t)$ accumulated in the capacitor, measured at room temperature without heating the cable, as a function of elapsed time t after the start of voltage application. Figs. 5(a) and 5(b) show the results obtained when the relatively low voltages from 0.2 to 2 kV and the relatively high voltages from 4 to 20 kV were applied, respectively. Immediately after the voltage application, $Q(t)$ increases sharply regardless of the applied voltage. While it increases linearly after that, the rate of increase or the slope of the

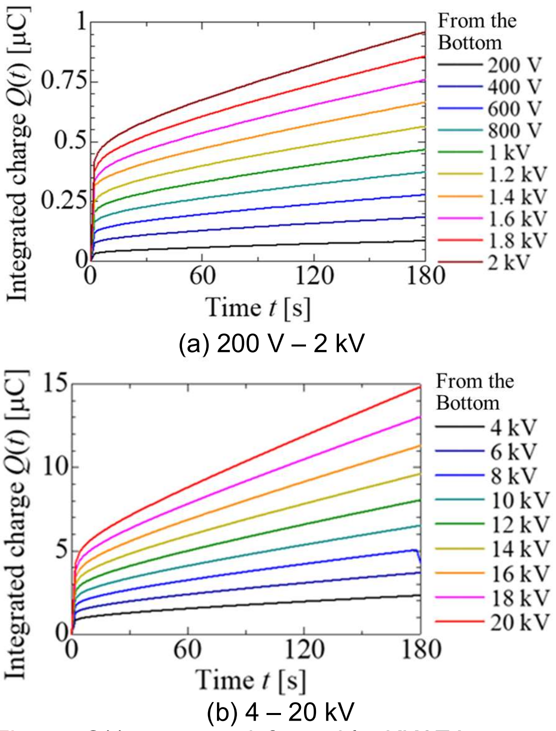

Fig. 5. $Q(t)$ measured for cable KK6EA at room temperature.

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$Q(t)$ curve increases as the applied voltage becomes higher, indicating an increase in the leakage current.

Next, $Q(t)$ was measured for the same cable KK6EA while partially heated to 80 °C and is shown in Fig. 6(a) for 0.2 to 2 kV and Fig. 6(b) for 4 kV and above. Here, the measurement was stopped halfway during the application of 8 kV to protect the measuring equipment. Note that the range of the ordinate is completely different between Figs. 5 and 6, reflecting the difference in whether the cable was heated partially or not.

As mentioned above, Q_0, which sharply increases immediately after voltage application, is the so-called instantaneous charge given by the product of the capacitance of the capacitor and the applied voltage. As an example, when 2 kV is applied, the charge $Q(2)$ after 2 s of voltage application is 419 nC in the unheated measurement shown in Fig. 5(a), whereas it is 670 nC in the heated measurement in Fig. 6(a). Assuming that the change in cable shape due to thermal expansion during the heating is negligible, the permittivity is approximately 1.6 times higher in the heated measurement than in the unheated measurement. We reported, in our previous paper [10], that the permittivity of FR-EPDM for cable insulation in NPPs clearly depends positively on the temperature at low frequencies, whereas it hardly depends above 100 Hz. That is, the possibility is affirmed, at least qualitatively, that the permittivity of the cable insulation is increased during the heated measurement.

To avoid such influence of the change in the permittivity of the cable insulation, we will consider the charge ratio $Q(180)/Q_0$. Figs. 7(a) and 7(b) show the charge ratios acquired for cable KK6EA by the unheated and heated measurements, respectively. It is evident by comparing the two figures that partial heating at 80 °C significantly increases the charge ratio.

As will be mentioned later, we do not believe that the present data of the charge ratio measured for the cable KK6EA reflect any degradation of the cable insulation. Fig. 7 indicates that the leakage current becomes higher when we heat the cable, as expected in Section II-B. This means that we can have a higher detection sensitivity of any change in the insulation resistance of the cable at higher temperatures. Assuming that we use this method for examining cable insulation, when we scan a ribbon heater to heat the cable and the heater hits a degraded portion, we can find the degradation more clearly than using no heaters. Therefore, our heating-assisted current integration method can be a good condition monitoring tool for cable insulation.

B. Cables KK6EB and KK6EC

Next, we pay attention to the results acquired for cables KK6EB and KK6EC, which were installed in slightly milder environments than KK6EA. Their results are similar to those of KK6EA described in the previous section, except for some details. For this reason, the temporal change of $Q(t)$ is not shown, and only the applied voltage dependence of the charge ratio is shown.

Fig. 8 shows the results obtained for KK6EB by the unheated measurement when voltages from 0.2 to 20 kV were applied

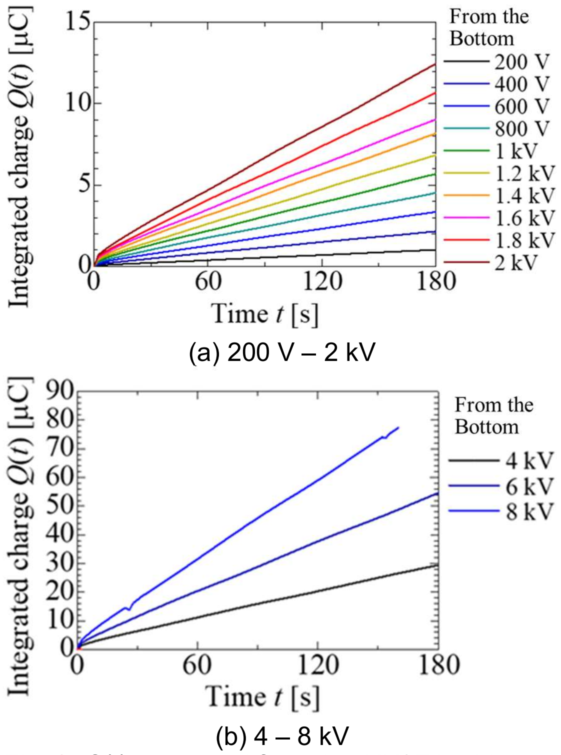

Fig. 6. $Q(t)$ measured for cable KK6EA while partially heated to 80 ℃.

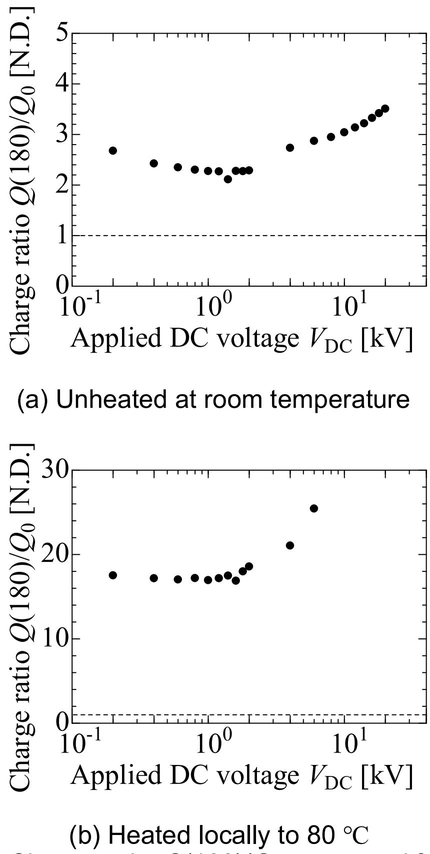

Fig. 7. Charge ratio, $Q(180)/Q_0$, measured for cable KK6EA at room temperature (a) and while heated locally to 80 ℃ (b).

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and by the heated measurement when voltages from 0.2 to 6 kV were applied. In addition, Fig. 9 exhibits those obtained for KK6EC by the two measurements when the same voltages as for Fig. 8 were applied. In both figures, for all applied voltages, the charge ratio is clearly larger in the heated measurement at 80 °C than in the unheated measurement at room temperature. The reproducibility of the phenomenon mentioned concerning cable KK6EA is confirmed. Namely, the adoption of partial heating significantly enhances the detection sensitivity of the change in insulation characteristics by the current integration method.

IV. Discussion

A. Dependence of Q(t) on the Applied Voltage

In Figs. 7(a) and 7(b), the charge ratio stays almost constant or gradually decreases as the applied voltage increases until it reaches 2 kV for the unheated measurement or up to 1.6 kV for the heated measurement. Similarly, in Figs. 8 and 9, the charge ratio hardly depends on the applied voltage until it reaches 2 kV in the unheated measurement or 1.6 kV in the heated measurement.

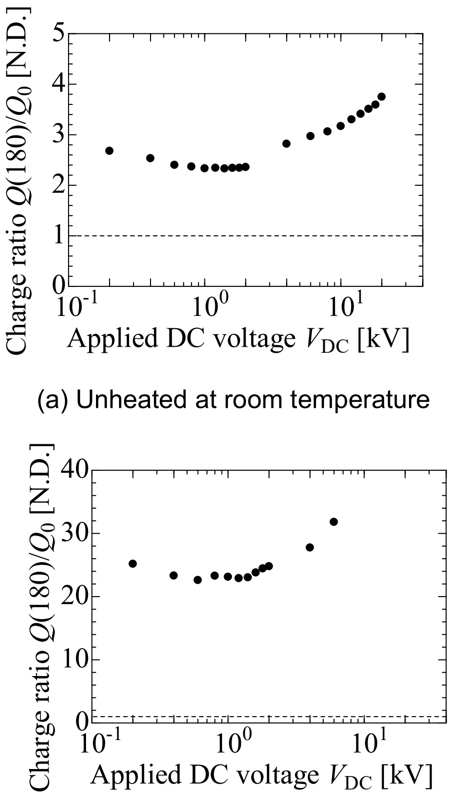
The three cables used in this research have five cores, and as shown in Fig. 1, each core conductor covered with an FR-EPDM insulator is arranged in the circumferential direction and their gaps are filled with intervention. Furthermore, an FR chloroprene rubber sheath is placed on their outer circumferences. Therefore, the electric field distribution inside the cable is complicated. However, we can simplify the electric field distribution if we assume that the electrical resistivity of the intervention is much lower than that of the insulator and sheath. Then, almost all of the applied voltage is applied to the insulators of the red and black cores, and the electric potential becomes equal in the electrically floating white, green, and yellow cores and the intervention. Therefore, in an electromagnetic sense, the red and black cores can be regarded to have a simple coaxial cylindrical structure consisting of the central conductor and the outer insulator. Half the applied voltage is applied to each insulator in the red and black cores, and the potential inside the red or black insulator becomes the same on each surface concentric with the conductor.

Here, assume that an insulator with permittivity ε and conductivity σ is sandwiched between two coaxial electrodes with length l, inner radius r_1, and outer radius r_2 to form a capacitor. Then, the capacitance C of the capacitor is given by (1) [26],

$$C = 2\pi\varepsilon l / \log_e \frac{r_2}{r_1} \quad \text{[F]}, \qquad (1)$$

while the leakage conductance G between the two electrodes is given by (2) [26],

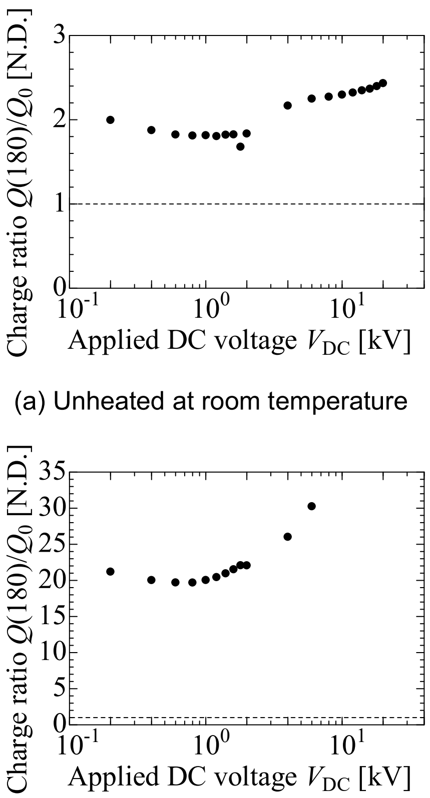
$$G = 2\pi\sigma l / \log_e \frac{r_2}{r_1} \quad \text{[S]}. \qquad (2)$$



(a) Unheated at room temperature

(b) Heated locally to 80 °C

Fig. 8. Charge ratio, $Q(180)/Q_0$, measured for cable KK6EB at room temperature (a) and while heated locally to 80 °C (b).



(a) Unheated at room temperature

(b) Heated locally to 80 °C

Fig. 9. Charge ratio, $Q(180)/Q_0$, measured for cable KK6EC at room temperature (a) and while heated locally to 80 °C (b).

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Therefore, when the potential difference between the electrodes is φ, the initial charge Q_0 stored in this capacitor and the leakage current I flowing between the electrodes are respectively given by (3),

$$Q_0 = C\,\varphi = 2\pi\varepsilon l\varphi/\log_e\frac{r_2}{r_1} \quad [\mathrm{C}], \qquad (3)$$

and (4),

$$I = G\,\varphi = 2\pi\sigma l\varphi/\log_e\frac{r_2}{r_1} \quad [\mathrm{A}]. \qquad (4)$$

If a constant leakage current expressed by (4) flows during the entire period of voltage application time t, $Q(t)$-Q_0 becomes

$$Q(t) - Q_0 = I\cdot t = 2\pi\sigma l\varphi t/\log_e\frac{r_2}{r_1} \quad [\mathrm{C}]. \qquad (5)$$

Therefore, if the leakage current is constant over time, $Q(t)-Q_0$ naturally increases in proportion to the applied voltage and voltage application time. Equation (5) agrees with the changes in $Q(t)$ shown in Figs. 5 and 6.

B. Estimation of Leakage Resistance

Cable KK6E is for low voltages, intended for AC voltages of 600 V or less and DC voltages of 750 V or less. Since a DC voltage of 750 V was not applied in this study, the leakage current is estimated from the experimental results when a slightly higher voltage of 800 V was applied. As shown in Table 1, the temperature of the environment in which the cable was placed is approximately 50 °C or less. Regarding this, the leakage current is estimated using the experimental results when the cable was heated partially to a higher temperature of 80 °C.

In Fig. 6(a) showing the change in $Q(t)$ for cable KK6EA, the amount of charge Q_0 or $Q(2)$ after 2 s of application of 800 V is 263 nC, whereas $Q(20)$ after 20 s, in which the change in $Q(t)$ over time can be considered sufficiently linear, is 771 nC. On the other hand, the final measured charge $Q(180)$ is 4522 nC. The leakage current calculated from these values is 23.9 nA when using $Q(2)$, while it becomes 23.4 nA if we use $Q(20)$. DC 800 V was applied between the red and black cores in this experiment, as described above, meaning 400 V to the insulator of each core. Therefore, the insulation resistance is calculated to be 16.7 to 17.1 GΩ from the above current values. This indicates there is no need to pay much attention to the selection of the initial charge Q_0 if we choose an appropriate elapsed time in a range of 2 to 20 s or so.

The insulation resistance of a cable circuit is inversely proportional to the length of the cable. The cable used in the experiment is 2 m. Assuming that this cable is used in a circuit with a length of 50 m in a reactor containment vessel, the insulation resistance of the corresponding circuit becomes about 670 MΩ. On the other hand, according to a Japanese ministerial ordinance determining technical standards for electrical equipment [27], the insulation resistance required for low-voltage circuits with a maximum working voltage of 330 V or above is 0.4 MΩ. With this respect, the above 670 MΩ is more than 1600 times this value.

Although not described in detail, very similar results can be obtained with cables KK6EB and KK6EC. The present experiments yield only literal trial calculations since a quarter length of the 2 m cable was heated to 80 °C. Nonetheless, it is judged that the above calculations exhibit that the cable removed from the containment vessel has sufficient insulation performance.

C. Evaluation of Conductivity by Charge Ratio

From (3) and (5), we obtain

$$\frac{Q(t)}{Q_0} = 1 + \left(\frac{\sigma}{\varepsilon}\right)t, \qquad (6)$$

which is transformed into

$$\sigma = \left(\frac{Q(t)}{Q_0} - 1\right)\left(\frac{\varepsilon}{t}\right) \quad [\mathrm{S/m}]. \qquad (7)$$

Equations (6) and (7) are very general and hold, irrespective of whether the above assumption that the resistivity of the intervention is much lower than that of the insulator and sheath is correct. From (6), the charge ratio does not depend on the value of the applied voltage as long as σ and ε are constant, although it increases linearly with the voltage application time.

Let the charge ratio of $Q(180)/Q_0$ measured for cable KK6EA when its part was heated, shown in Fig. 7(b), be assumed to be 19 at the voltage application of 800 V. If a constant leakage current flows throughout the whole measurement period of the current integration method, σ at t = 180 s becomes as follows from (7):

$$\sigma = 0.1\varepsilon \quad [\mathrm{S/m}]. \qquad (8)$$

We reported in our previous paper that the relative permittivity of FR-EPDM at 80 °C was measured to be about 3.9 at 10 mHz [10]. Regarding this, the relative permittivity of FR-EPDM for DC voltages is assumed to be 4.0 at 80°C since it gradually increases with the decrease in frequency at 80°C [10]. Then, from (8), σ at t = 180 s becomes

$$\sigma = 3.54 \times 10^{-12} \quad [\mathrm{S/m}]. \qquad (9)$$

We substitute this σ into (2). Here, the cable constants are l = 2 m, r_1 = 0.8 mm from the nominal cross-sectional area of 2 mm^2, while r_2 = 1.6 mm by adding the insulation thickness of 0.8 mm to r_1. As a result, the insulation resistance of the cable sample insulated with FR-EPDM of the length of 2 m at 80 °C is obtained as $(1/G)$ = 15.6 GΩ as the reciprocal of G in (2).

The above value of the insulation resistance, 15.6 GΩ, matches well with the values of 16.7 to 17.1 GΩ, directly calculated from the changes in $Q(t)$ over time. There is an aspect to say that this agreement is natural since the two calculations are originally based on the same experimental results. The charge ratio $Q(t)/Q_0$ is, of course, a function of voltage application time t. However, since ($Q(t)/Q_0$ -1) is proportional to t, (7) gives, irrelevantly to t, an estimate of the conductivity σ of the insulator.

Based on the above, the measurement results of the charge ratios shown in Figs. 7 to 9 will be considered. In both the cases of non-heating and partial heating, when a relatively low voltage is applied, the charge ratio shows a substantially constant value regardless of the applied voltage. On the other hand, when a relatively high voltage is applied, the charge ratio tends to increase as the applied voltage increases. That is, the conductivity σ is constant in the low voltage range but increases at high voltages. A comparison between the results acquired by the non-heating and partial heating methods has shown that the high

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electric field region, where the charge ratio increases as the applied voltage is higher, begins at a lower electric field at high temperatures.

D. Differences among the Three Cable Samples

As mentioned in the previous section, (7) gives an estimate of the conductivity σ of the insulator. Based on this, the comparison of the measurement results of each sample shown in Figs. 7 to 9 will be considered. When a relatively low voltage of up to 2 kV is applied, the charge ratio, $Q(180)/Q_0$, measured at the end of the partial heating measurement is approximately 16 to 18 in Fig. 7(b) for cable KK6EA, 22 to 26 in Fig. 8(b) for KK6EB, and 19 to 23 in Fig. 9(b) for KK6EC. Therefore, the magnitude of σ of insulation in each cable sample is estimated to be

$$\text{KK6EA} < \text{KK6EC} < \text{KK6EB}. \quad (10)$$

On the other hand, according to Table I, the environment in which each cable was laid is

$$\text{(Mild) KK6EC} < \text{KK6EB} < \text{KK6EA (Severe)}. \quad (11)$$

If σ of the cable insulation is positively correlated with the severity of the installation environment, the magnitude relationship should match in (10) and (11). On the other hand, we have already reported that the electrical insulation performance of FR-EPDM insulated cables removed from a pressurized-water NPP has been improved over the time of its installation in the nuclear environment [2]. The reason for the above is that FR-EPDM becomes hardened by aging, which hinders the migration of ions, the dominant carrier species of electrical conduction [2]. If the same holds for the cables removed from the boiling-water NPP in this study, (10) should be the opposite of (11). However, (10) is neither in the same direction as (11) nor in the opposite direction.

As a consequence of the above, it should be judged that there is no significant difference in the severity of the environment listed in Table I, in which the three cables were laid, with respect to the effect of the environment on the insulation resistance of the cables. Therefore, neither the charge ratios shown in Figs. 7 to 9 nor the order of the magnitude of σ estimated resultantly, shown in (10), reflects the differences in the severity of the installation environment of each cable sample. In relation to the above judgment, the results of this research show that the charge ratios shown in Figs. 7(b) to 9(b), acquired by the partially heated measurements, are higher than those shown in Figs. 7(a) to 9(a) by the non-heated measurements. In other words, the reproducibility is confirmed concerning the fact that the leakage current of the cable insulation is easily measurable by the partial heating method.

As the operation period of NPPs becomes longer, the importance of detecting the degradation of cable insulation is increasing. As for the position-locating method of the degradation of cable insulation, the authors have also been working hard to develop a method that has been evaluated as having a high positional resolution at the laboratory level [28-30], although the feasibility of its application to actual NPPs is under investigation. The current integration method combined with partial heating, which was attempted in this research, is considered a method for locating insulation degradation, which is practically usable immediately if we can approach the cable.

V. Conclusion

Three cables insulated with FR-EPDM were harvested from the boiling-water NPP, and DC voltages were applied to measure the leakage current by the current integration method. Two cases were used for the measurements: the whole cable with the length of 2 m was placed at room temperature, and a section of 50 cm in length was heated to 80 °C. As a result, it has been confirmed that, in all cables at all applied voltages, a remarkably higher leakage current was induced when partially heated to 80 °C than when measured by holding the entire cable length at room temperature. This means that the detection sensitivity of variations in insulation characteristics of FR-EPDM cables by the current integration method is enhanced significantly by partial heating. Further, this indicates that the current integration method combined with partial heating can be a location method for the insulation degradation of cables.

Next, it has been explained that the ratio of the amount of charge stored in the measurement capacitor at the end of the measurement to its initial amount, both measured by the current integration method, represents the conductivity of the sample cable. In addition, it has been confirmed that the removed cables maintain significantly higher insulation resistance than the value set in the relevant ministerial ordinance.

Although the cable examined in this research is rather specific with five cores, the resultant findings mentioned there, such as the effect of aging on FR-EPDM insulation and the effectiveness of the heating-assisted current integration method, have broad generality.

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