$$Q(t) = \sum_{i \in S} Q_i(t)$$

where

$S = \{\text{disp}, \text{abs}, \text{cond}\}$

Role and Future Perspective of Current Integration Method for the Evaluation on Dielectric and Insulating Properties

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This paper focuses on the "Current Integration Method (Q-t method)," widely used in Japan in recent years, to understand the electrical conduction and space charge behavior of insulating materials, in conjunction with the advancement of high voltage direct current (HVDC) technology and polymer insulation technology. The Q-t method involves connecting an integrating capacitor to the sample in series and measuring the integrated small currents passing through it. The advantage of this method is that it allows comprehensive and panoramic observation of electrical phenomena, and by applying this advantage to dielectric measurements, it enables a wide range of applications such as condition monitoring, understanding the limits of insulation material usage, material selection and evaluation. This paper provides examples of its applications and highlights its unique advantages and functionality.

Keywords: dielectric/insulating materials, current integration method (Q-t method), screening, condition diagnosis

1. Introduction

Electrical insulating materials are essential for electrical power equipment and various home appliances in our daily lives. In recent years, the use of direct current (DC) in equipment for generating and transmitting electric power has been increasing. Understanding and controlling the dielectric and insulating properties of such materials under DC voltage has become an important technical issue for researchers and engineers. In addition, even for equipment used with conventional alternating current (AC), there is a need to develop effective condition diagnosis techniques from the perspective of equipment maintenance.

In these seemingly diverse technical fields, the common denominator is the importance of understanding "dielectric and insulating properties." Conventionally, these measurements have been performed using separate methods. However, even though they may appear to be separate characteristics, as there is a physical connection between them, complementary and comprehensive measurements can lead to a better understanding of individual measurement results and avoid misunderstandings. The current integration method (Q-t method)*1 is an excellent method from this perspective. In this review we will discuss the applications of the Q-t method reported so far and describe possible future developments.[1]

2. Features of the Q-t Method

As reported twice before in the Sumitomo Electric Technical Review,[(2)-(3)] the main advantage of Q-t method is that various information can be obtained with a simple operation. There are also many advantages gained by "integration*2"; the features of the Q-t method can be summarized as follows:

(A) Random noises are canceled by integration, thus suppressing the effect of random noise.
(B) Measurement by the Q-t method is independent of the shape and arrangement of the electrodes.
(C) Comprehensively evaluate physical phenomena involving current components (injection, accumulation and migration of space charge, electrical conduction, etc.).
(D) Integration allows for a clear measurement of the initial value, $Q(0)$ ($=C_s V_{DC}$).
(E) By using $Q(0)$, the new parameters "charge ratio ($R_c = Q(t_m)/Q(0)$)" and "charge difference ($D_c = Q(t_m) - Q(0)$)" are defined, which are useful for understanding dielectric properties.

3. Applications

By making good use of the features of the Q-t method, the following applications are possible. First, in the industrial field,

(1) Screening of materials and products from a broad perspective of dielectric properties
(2) Condition monitoring using integrated small currents

By adding features (D) and (E) to the features (A) through (C) listed in section 2, the meaning of the data changes from planar to more perspective.

Also, in academic and basic fields, mainly in electro-physics, the following is given:

(3) Analysis of physical phenomena related to current components

The former is in the same procedure as the latter, however, it is necessary to understand the characteristics of polymers used as insulating materials and to devise analytical methods with the help of mathematics and physics. It should be considered that the area of this field is relatively deep and broad. If effective analytical methods can be developed, the results of basic innovations may be returned to the industrial field.

Some examples of actual applications of the Q-t method, with a focus on the content summarized in the reference[1] are written below.

3-1 Material screening

Usually, the dielectric properties of polymer insulating materials are obtained separately using the appropriate method for each phenomenon. When a square wave voltage*3 is applied, the charge amount measured by the Q-t method can be expressed in three components as shown in Eq. (1).

$$Q(t) = \sum_{i \in S} Q_i(t) = Q_{\mathrm{disp}}(t) + Q_{\mathrm{abs}}(t) + Q_{\mathrm{cond}}(t) \quad \cdots \text{(1)}$$

where, S = {disp,abs,cond}

Here, $Q_{\mathrm{disp}}(t)$ is the instantaneous charge amount, $Q_{\mathrm{abs}}(t)$ is the absorption charge amount, and $Q_{\mathrm{cond}}(t)$ is the conduction of charge amount, representing the charge amount when the sample is regarded as a capacitor ($=C_s V_{\mathrm{DC}}$), the charge amount mainly due to injection, accumulation and migration of space charge, and the charge amount due to electrical conduction in the sample, respectively. Since this is an instantaneous phenomenon at the initial stage of applying voltage, $Q_{\mathrm{disp}}(t)$ will henceforth be expressed as $Q(0)$.

The Q-t method measures and analyzes these charge components with a single and simple treatment.

First, consider $Q(0)$, the initial rising portion of $Q(t)$ that occurs just after the application of the square wave voltage. If the current response for voltage is linear, $Q(0)$ is proportional to the applied voltage V_{DC}, so it is very important to check the linearity of $Q(0)$ with respect to V_{DC}. Since $Q(0)$ includes the capacitance Cs, the electrostatic permittivity ε can be obtained. And as shown in Fig. 1 (a), no conduction current or absorption current flows in the sample, R_c remains at "1".

Second, consider the $Q(t)$ profile in a steady state. When only conduction current flows in the sample, taking the charge ratio R_c ($=Q(t)/Q(0)$) on the vertical axis, as shown in Fig. 1 (b), R_c shows a linear variation with t and the slope of the $Q(t)$ curve is equal to the conduction current $I_{\mathrm{cond}}(t)$ ($=\mathrm{d}Q(t)/\mathrm{d}t$). From $I_{\mathrm{cond}}(t)$, the electrical conductivity κ is obtained[2].

Finally, we consider transient phenomena in the $Q(t)$ profile at the initial stage of voltage application. At this stage, an absorption component due to transient charge behavior is detected. Taking the charge ratio R_c on the vertical axis, a curve like that in Fig. 1 (c) is obtained where the transient absorption charge component is included and the deviation from the conduction charge component is added on the curve of Fig. 1 (b). By analyzing this curve, information on the absorption charge component can be obtained.

Needless to say, these procedures need to be performed under different temperature and electric field conditions in order to understand the temperature and electric field dependence of dielectric properties.

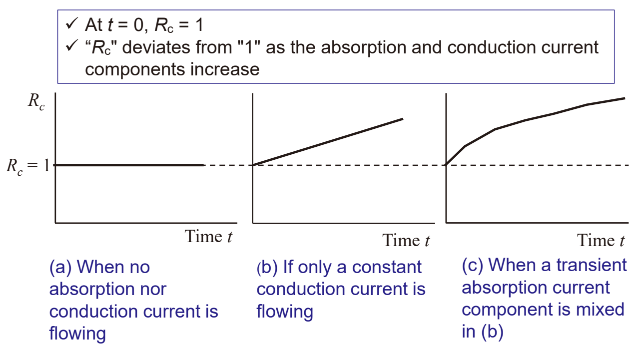


Fig. 1. Image of $Q(t)$ profile
(a) no absorption nor conduction currents, (b) only constant conduction current, and (c) absorption and conduction currents

3-2 Cable condition diagnosis

Power cables (especially distribution cables) that do not have a waterproof layer to prevent water immersion from the outside is prone to a form of insulation degradation known as water-tree degradation, and many studies have been conducted to detect an early stage of the degradation by condition monitoring. The DC leakage current method is one of such condition monitoring methods.[4] This method enables us to detect water-tree that bridges insulators (expressed as the growth of water-tree to the extent that it connects the inner and outer semiconducting layers), but it is difficult to detect water-tree that does not bridge insulators. A method using the Q-t method for measuring DC leakage currents has been studied by Kurihara and others.[5] In the study, an accelerated water tree degradation test was performed on two types of removed cables[6] and one new cable, and obtained three types of the cables with different degrees of degradation (cables 1 to 3, where cable 1 is severely degraded, cable 2 is moderately degraded, and cable 3 is mildly degraded) were used to compare the conventional method, the DC leakage current method, with the Q-t method. As a result, cable 1, which was severely degraded and had the aforementioned bridging water-tree, was diagnosed as having an abnormality by the conventional method, but light and moderate degradation could not be distinguished. In contrast, the three degradation degrees could be distinguished by the Q-t method, as shown in Fig. 2. This result indicates that the Q-t method has the potential to discriminate even the degree of degradation.[5]

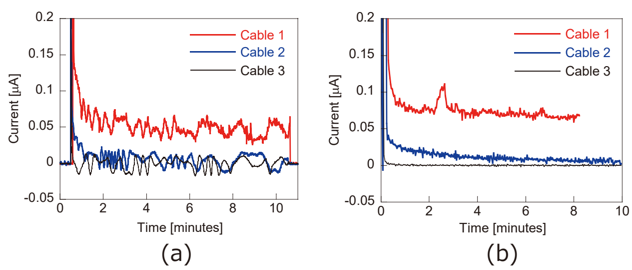


Fig. 2. Comparison of leakage currents of cables samples 1-3[5]
(a) Conventional DC leakage current method and (b) Q-t method

3-3 Thin films

In the field of organic electronics and in film capacitors, very thin polymer films are often evaluated. The Q-t method is also suitable for the evaluation of electrical conduction and space charge behavior in these thin films.

Typically, the thinner the film sample, the more difficult it is to measure space charge behavior. The pulsed electro-acoustic (PEA) method is an effective method for evaluating charge behavior and is unique in its ability to measure the distribution of charges within a sample. However, due to limitations of resolution, it cannot be applied to extremely thin films of less than 10 µm. The Q-t method is effective in such cases. Although the Q-t method cannot measure the charge distribution in the thickness direction of the sample, it can accurately measure the total charge in the sample. Measuring time, temperature, and electric field dependence of $Q(t)$ can help us investigate the charge behavior within the sample.

3-4 Power module

Electrical and electronic devices often have complex structures with nonlinear electric fields. However, even in such cases, the Q-t method can provide effective and useful insights.

Mima et al. evaluated commercially available power electronic devices, such as IGBT modules and diode bridges, by applying square wave voltages from 100 to 4000 V in the range from room temperature to 80°C.(7) Temperature-dependence of charge ratio R_c (=$Q(t)/Q(0)$) was evaluated for the IGBTs, as shown in Fig. 3. The figure shows that at room temperature and 40°C, R_c is approximately 1, indicating that the charge supplied from the DC power source is almost induced and accumulated near the electrodes, with no injection or transfer to the insulation layer occurring. On the other hand, at 60°C, R_c is 1.5 in the range of 500 to 4000 V, indicating that the injected charge from the electrodes may have accumulated in the insulating layer of the IGBT module, the so-called absorbed charge. Furthermore, at 70°C and 80°C, R_c exceeds “2,” indicating that the conduction current is likely to be more dominant than the absorbed current in this region. Therefore, since the Q-t method can be applied to devices other than power cables, it is expected to significantly increase its use in the evaluation of various electrical and electronic devices and their insulating materials.

(Note: Considering an ideal system in which the charge injected from the electrode moves uniformly, R_c=1 when there is no charge injection nor transfer, but R_c gradually deviates from 1 when charge injection occurs. At this time, just R_c=2 represents that the dielectric relaxation time τ is equal to the measurement time t_m, which can be expressed electromagnetically as the filling of the trap site in the material.(8) Therefore, we can assume that electrical conduction is dominant at R_c >2. (It should be added, however, that this model assumes ideal, uniform charge movement and is only a guide.)

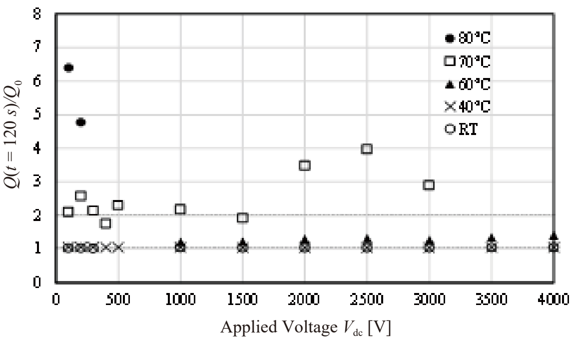


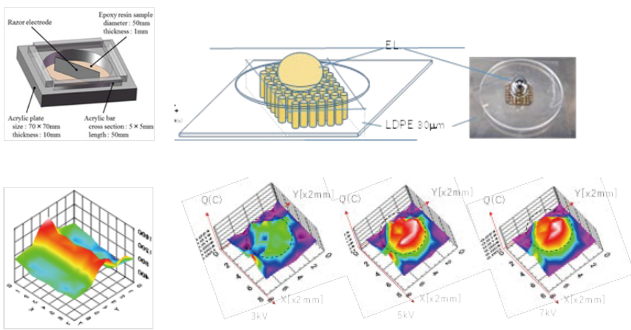
Fig. 3. Temperature dependence of charge ratio on applied voltage for IGBT module sample(7)

3-5 Phenomenological understanding of dielectric and insulating phenomena

Some of the features of the Q-t method bring advantages for the scientific and technical evaluation of polymer insulators. The most important features are that, compared to small current measurements, integration can reduce random noises, and the Q-t method allows defining and obtaining the initial value of $Q(t)$ when a square wave voltage is applied. These features allow us to find overarching and complementary trends in $Q(t)$ profiles. Some examples are shown below.

(1) Multi-channel Q-t measurement system

By utilizing the features of the Q-t method, it is expected that $Q(t)$ can be measured with high accuracy even with small-sized electrodes. Fukuma et al. constructed a multi-electrode system (multi-channel) Q-t meter with 60 electrodes, each 1.5 mm in diameter, to measure charge and current distribution under non-uniform electric fields, such as blades, spheres, or rod-shaped electrodes.(9),(10) Figure 4 shows the measurement results of the blade and sphere electrode when a square wave voltage is applied. It is found clearly that the charge is accumulated at the tip of the blade electrode. However, in the case of the sphere electrode, the charge is not accumulated at the tip of the electrode. Therefore, this method is expected to be particularly useful for charge accumulation and current distribution in non-uniform electric fields.



(a) Blade electrode (b) Sphere electrode

Fig. 4. Charge distribution under non-uniform electric field(9),(10) (a) blade electrode and (b) sphere electrode

(2) Analysis using triangular wave voltage

The techniques described in the previous sections used square wave voltage as the DC voltage to be applied, but useful findings can be obtained with voltages other than square wave. Fukuma et al. used a triangular wave voltage*3 to perform Q-t measurements on polymer film samples.(11)

If $I(t)$ is measured by changing the voltage at a constant rate, the instantaneous charging current component is expressed as $C_s dV_{DC}(t)/dt$. This value is constant as shown in Fig. 5 (a). The conduction current follows the same path for the applied voltage during boost and buck, as shown in Fig. 5 (b). On the other hand, the absorption current component shows a nonlinear response to voltage as shown in Fig. 5 (c), increasing with an increase in voltage, and following different curves for boost and buck. Therefore, when the absorption current component and the conduction current component are added together, the response can be considered to diverge from the path of the conduction current component as the absorption current component increases, as shown in Fig. 5 (d).

$$I(t) - C_s \frac{dV_{DC}(t)}{dt} = I_{abs}(t) + I_{cond}(t) \quad \cdots\cdots\cdots\cdots (2)$$

In the end, the area bounded by the curves in Fig. 5 (d) for boosting (red line) and for lowering (green line) is considered to be the absorbed charge component. Figure 6 shows the actual measurement results in LDPE.

Integrating both sides of Eq. (2) yields the relationship for the amount of charge $Q(t)$, as shown in Eq. (3), and the total amount of absorbed and conducted charge can be directly obtained.

$$Q(t) - C_s V_{DC}(t) = Q_{abs}(t) + Q_{cond}(t) \quad \cdots\cdots\cdots\cdots (3)$$

Thus, the triangular wave voltage can be used to qualitatively determine information about the electrical conductivity and space charge behavior of a sample in a shorter time.

(3) Electrical Conduction and Space Charge Behavior Analysis

The feature of suppressed random noise effects in the Q-t method offers several advantages for the measurement of dielectric and insulation properties. The results of current measurements on a sheet sample of ordinary cross-linked polyethylene (AC-XLPE) for power cables of 0.2 mm thickness are shown in Fig. 7 (a). The lower the temperature and electric field, the more difficult it becomes to measure small currents. However, by using the integration of $I(t)$ by the Q-t method, much more stable curves of $Q(t)$ data can be obtained as shown in Fig. 7 (b), and tendencies in current can be clearly observed as the slope of each $Q(t)$ curve. The similarity of each $Q(t)$ curve suggests the existence of a time-temperature or time-electric field superposition principle. An example of applying the time-temperature superposition principle to $Q(t)$ curves is shown in Fig. 8.[12] The factor that converts real time to converted time is called the shift factor. The physical meaning of the obtained shift factor needs to be analyzed in detail, and it is expected that new discoveries will be made as a result.[13]

4. Future Advancement

As we have seen in the paper, the Q-t method can contribute to two major technical fields: industrial fields such as power cables and basic and academic fields that deal with small currents, mainly in the field of electro-physics.

As for contributions to the industrial field, as mentioned here, studies have already begun on the Q-t method as a diagnostic method for the condition moni-

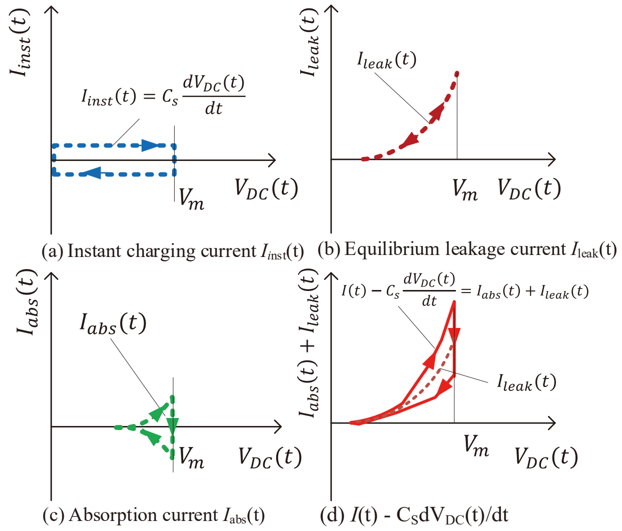


Fig. 5. Image of current response when triangular wave voltage is applied[11]

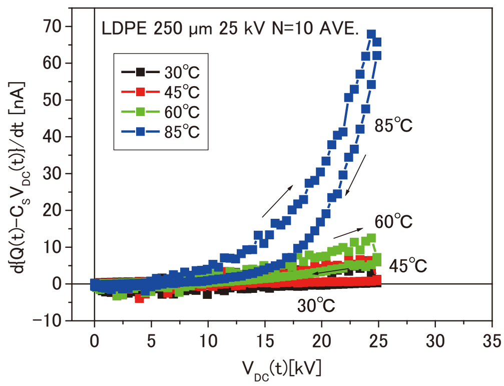


Fig. 6. Voltage dependence of $I(t) - C_s \frac{dV_{DC}(t)}{dt}$ when triangular wave voltage applied to LDPE[11]

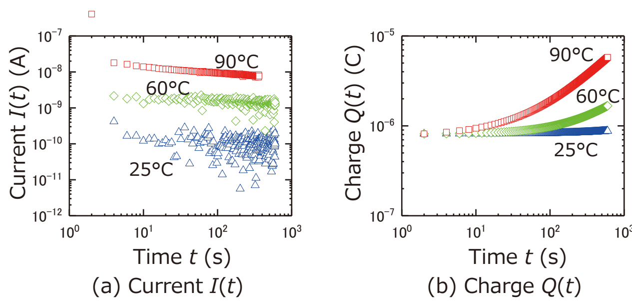


Fig. 7. $I(t)$ and $Q(t)$ profiles of AC-XLPE under 75 kV/mm[12]

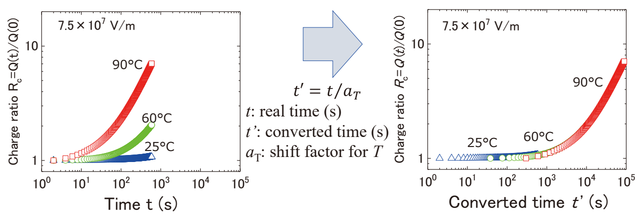


Fig. 8. An example of the time-temperature superposition principle to AC-XLPE R_c-t data[12]

toring of cable insulation. However, currently, this method is being tested on cable samples that have been removed, with the main focus being on accurately determining the degree of degradation of these samples. Its application to actual cable lines for evaluation has not yet been achieved. If a measurement device with a capacitor is placed on the ground side, the sample will be measured in an electrically floating state. To avoid this, the equipment can be placed on the high-voltage side, but this exposes the equipment to high potentials, necessitating the implementation of countermeasures. Although there are numerous challenges in applying this method to actual cable lines, if a solution can be found, it could prove to be a valuable diagnostic technique for actual application.

When it comes to its application in academic fields, the Q-t method can provide a unique perspective for analyzing electrical conduction phenomena, that surpasses conventional methods, if the features of the Q-t method described here are fully utilized. To fully make use of the Q-t method, it is necessary to consider not only from the standpoint of electromagnetism but also from physical and chemical perspectives, taking into account the specific characteristics of the polymers used as insulators. By adopting these comprehensive perspectives, the successful utilization of the Q-t method can be achieved.

5. Conclusion

With the advancement of high voltage direct current (HVDC) technology and polymer insulation technology, the demand for improved materials and evaluation techniques for HVDC equipment is increasing. Both existing and newly developed technologies need to be utilized for the further advancement of HVDC technology. In this regard, the Q-t method is a promising candidate to achieve this goal.

The most attractive feature of the Q-t method is its ability to provide a comprehensive and complementary understanding of dielectric and insulation performance. This capability is particularly evident when the Q-t method is used in conjunction with other evaluation methods, as it helps to avoid incomplete or erroneous interpretation of experimental data. Another important feature of the Q-t method is its effect on integration. By integrating the current, the method improves tolerance to random noise and clarifies the integration constant as an initial value. The former feature allows the measurement of minute currents in a relatively simple manner, while the latter is useful in the process of analyzing insulation properties. This paper presents several potential applications of the Q-t method.

We believe that the effective and active utilization of the Q-t method will contribute to the advancement of HVDC technology. Furthermore, we believe that further development of scientific analysis methods using the Q-t method will lead to improvements not only in HVDC technology but also in conventional AC technology and other equipment besides power cables.

Technical Terms

*1 Current integration method (Q-t method): In previous papers, the term "direct current-integral charge method (Q(t) method)" was used, but this has been changed to the current integration method (Q-t method) in accordance with a move to unify terminology in the IEEJ.

*2 Integration: The term "integration" is used here to refer to the measurement of the current I(t) as the amount of charge Q(t) in an integrated capacitor. Note that it does not carry the mathematical meaning of integrating the measured value.

*3 Square wave voltage/Triangular wave voltage: A form of voltage in which a predetermined DC voltage is quickly applied and maintained is called a square wave voltage. On the other hand, a form of voltage that varies at a constant rate of increase (decrease) is called a ramp voltage. A ramp voltage that increases to a predetermined voltage Vmax and then decreases is called a triangular wave voltage due to its shape over time.

References

(1) Y. Sekiguchi, T. Kurihara, H. Miyake and T. Takada, "Direct Current Integrated Charge Method as a Useful Tool for Dielectric Measurements," cigre2024 Paris Session, No.11055 (in press) (2024)

(2) Y. Sekiguchi, T. Takada, H. Miyake, and Y. Tanaka, "Evaluation of Insulation Materials under High Voltage by Direct Current Integrated Charge Method," SEI TECHNICAL REVIEW No. 87, pp. 59-64 (2018)

(3) Y. Sekiguchi, K. Hosomizu, T. Yamazaki, T. Takada, and Y. Tanaka, "Analysis and Elucidation of Space Charge and Electrical Conduction Behaviors of Cross-linked Polyethylene by Q(t) Method," SUMITOMO ELECTRIC TECHNICAL REVIEW No. 94, pp. 23-28 (2022)

(4) The Japanese Electric Wire & Cable Makers' Association, "Maintenance and inspection guidelines for high-voltage cables," Technical report No.116D (in Japanese) (2012)

(5) T. Kurihara, T. Sato, T. Yurugi, T. Noro, "Investigations of Effects of Cable Insulation Thickness and Water Immersion on AC Breakdown Voltage and Degradation Diagnostic Data and Possibility of Detection of Non-bridged Water Trees of Dry-cured and Extruded Three-layer (E-E Type) 6.6kV XLPE Cables," IEEJ Trans. PE, Vol. 140, No. 4, pp. 243-252 (in Japanese) (2020)

(6) T. Kurihara, T. Sato, Y. Kabasawa, and T. Nagashima, "Fundamental Study on Water-tree Degradation Diagnosis for Dry-cured and Extruded Three-layer (E-E Type) 6.6 kV XLPE Cables with Penetrated Water Tree," IEEJ, Trans. FM, Vol. 139, No. 4, pp. 226-233 (2019)

(7) M. Mima, D. Hanazawa, K. Hijikata, H. Miyake, Y. Tanaka, T. Takada, T. Inoue, "Electric charge accumulation properties in packaged insulation layer of power electronic devices by using direct current integrated charge method," IEEJ Trans. FM, Vol. 139, No. 4, pp. 197-204 (in Japanese) (2019)

(8) T. Takada, Y. Sekiguchi, Y. Tanaka, "Classification of Q(t) profiles to induced electrode charge, accumulated charge and leakage vurrent charge," IEEJ Trans. FM, Vol. 141, No. 4, pp. 245-251 (in Japanese) (2021)

(9) M. Fukuma, Y. Sekiguchi, "Current Distribution Measurement under Non-uniform Electric Field by Current Integration Meter," International Symposium on Electrical Insulation Materials (ISEIM2017), DM-3 (2017)

(10) M. Fujii, M. Fukuma, S. Mitsumoto, Y. Sekiguchi, "Deterioration Diagnosis of Epoxy Resin Evaluated by Current Integration Meter," International Symposium on Electrical Insulation Materials (ISEIM2017), P1-5 (2017)

(11) M. Fukuma, Y. Sekiguchi, "Measurement of Q(t) when triangular wave voltage is applied to polymer film," 52h Symposium on Electrical and Electronics Insulating Materials and Applications in Systems, GP(O)-15 (in Japanese) (2021)

(12) Y. Sekiguchi, O. Urakawa, T. Inoue, "Time-temperature and time-electric field correlation for integrated currents in XLPE," International Symposium on Electrical Insulation Materials (ISEIM2023), M-1 (2023)
(13) Y. Sekiguchi, O. Urakawa, T. Inoue, "Time-temperature and time-electric field superposition for integrated currents in polymer insulating materials: The role of charge injection and anomalous mobility," Macromolecules, Vol. 57, pp. 6769-6778 (2024)

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