Evaluation of Insulation Materials under High Voltage by Direct Current Integrated Charge Method

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Due to the development and wide-spread use of high-voltage direct current (HVDC) transmission and its related equipment, the evaluation of the dielectric properties of insulation materials under HVDC has become important. While the evaluation of electric properties is generally carried out using different methods appropriate for their specific purposes, the authors have found a relatively simple technique that can simultaneously evaluate multiple dielectric properties of a material, such as permittivity, space charge behavior, and electrical conductivity, using the direct current integrated charge method. This paper describes the principle of the method and measurement results of low- and high-density polyethylene and polystyrene.

1. Introduction

In line with the recent growing demand for high-voltage direct current power transmission, it has been increasingly important to evaluate dielectric and insulating materials when direct current (DC) voltage is applied. There has been a growing need to deepen the discussion about the phenomena of space charge and electric conduction in materials.

The weak current that flows in materials under high-voltage direct current (HVDC) is the key to understanding these phenomena. In the case that a square wave voltage is applied, the current that flows in materials can be classified into three categories: instantaneous charging current in the initial phase of electric charge (charge current that flows when an electrode and specimen are considered as capacitors); absorption current, which accompanies space charge accumulation and transfer; and leakage current after a steady state is attained.

Usually, the above mentioned currents are measured using different techniques that correspond to respective physical phenomena. For example, the space charge accumulation behavior, which is an important precursor phenomenon of material deterioration attributed to electric charge, has been widely evaluated using the pulsed electro-acoustic method (PEA method) since the 1980s.[1]

The PEA method is a superb technique that offers information about the position of the accumulated charges, but it is used only for charges whose transfer speeds are relatively slow. This method cannot cope with fast-moving charges and conduction phenomena.

The direct current integrated charge method is a technique for conducting measurement and analysis by accumulating the charge quantity (Q(t)), an integral value of electric current, in a measuring capacitor that is connected to a specimen in series.[2] Since a capacitor is used, all the current components can be evaluated comprehensively. Due to the simple measurement, this method is effective for quickly and generally grasping the dielectric and insulation characteristics of materials.[3],[4]

This paper provides a simple explanation of the direct current integrated charge method and presents the results of its application for some polymer materials. Possible future deployment is summarized at the end of this paper.

2. Direct Current Integrated Charge Method (DCIC-Q(t) Method)

In the direct current integrated charge method (hereinafter abbreviated as "DCIC-Q(t) method"), charge quantity Q(t) (i.e. the integral value of the current) is accumulated in a measuring capacitor that is connected in series to a specimen to make evaluations (see Fig. 1). When a square wave voltage is applied, the current is classified based on the physical phenomena and is represented by equation (1).

$$Q(t) = \int I(t)dt = Q_0 + \int I_{abs}(t)dt + \int I_{cond}(t)dt \cdots (1)$$

$$\text{Where, } Q_0 = \int I_{disp}(t)\,dt = C_s \cdot V_{dc}$$

This section describes a case where voltage V_{dc} is applied to a specimen whose capacitance is C_s. $I_{disp}(t)$ (i.e. instantaneous charge current), $I_{abs}(t)$ (i.e. absorption current), and $I_{cond}(t)$ (i.e. leakage current) correspond to the current depending on the charging when an electrode and specimen are considered as a capacitor, space charge accumulation and transfer, and electrical conductivity of the substance, respectively.

Thus, permittivity, space charge, and electrical conductivity, which are usually measured by different techniques, can be measured at the same time by measuring and analyzing these currents based on the DCIC-Q(t) method. The respective evaluation techniques are explained below.

2-1 Capacitance and permittivity

The startup voltage when the square wave voltage is applied is V_{dc}, and the capacitance of the specimen is C_s. The charge quantity during charging Q_0 that accumulates in the specimen due to V_{dc} can be expressed by $C_s \cdot V_{dc}$. Thus, when Q_0 is measured by the DCIC-Q(t) method, C_s can be
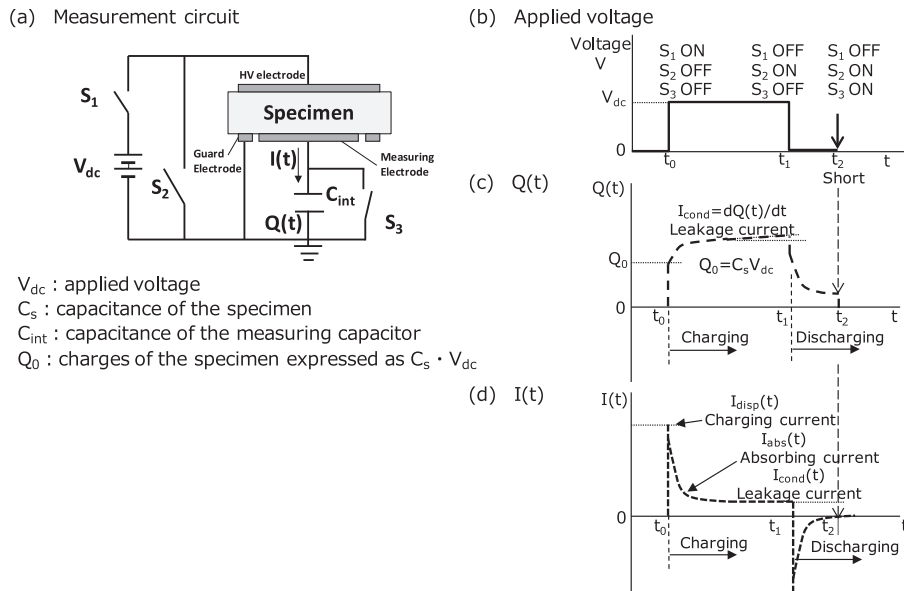
Fig. 1. Measurement circuit (a) and conceptual image of Q(t) and I(t) when a square wave voltage was applied ((b) to (d))

calculated.

$$Q_0 = C_s \cdot V_{dc} = \varepsilon S/d \cdot V_{dc} = \varepsilon_0 \varepsilon_r S/d \cdot V_{dc} \quad\cdots\cdots\cdots (2)$$

The relative permittivity ε_r can be calculated from C_s by using ε_0 (permittivity of vacuum), S (the electrode area), and d (the specimen thickness) (equation (2)).

2-2 Space charges

Information about space charge can be obtained based on the behavior of the absorption current that is affected by the space charge accumulation and transfer. It should be noted that, unlike the PEA method, the DCIC-Q(t) method does not provide information about the position of charge distribution. The DCIC-Q(t) method only offers information about the total charge quantity. To quantitatively calculate changes in the charge quantity, we evaluated the charge quantity ratio $Q(t)/Q_0$ (i.e. the ratio between the charge quantity $Q(t)$ at t seconds later and the charge quantity Q_0 immediately after startup).

$$\frac{Q(t)}{Q_0} = 1 + \frac{\Delta Q(t)}{Q_0} \quad\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Where, $\Delta Q(t) = Q(t) - Q_0 = \int I_{abs}(t)dt + \int I_{cond}(t)dt$

When charge quantity ratio $Q(t)/Q_0$ is 1, there is no injection or accumulation of charge to or in the specimen.

2-3 Electrical conductivity

Current can be calculated by differentiating the charge quantity by time ($dQ(t)/dt = I(t)$). Thus, the gradient of the time dependence graph of $Q(t)$ obtained in an experiment in the steady state shows the leakage current. Electrical conductivity κ can be calculated from the leakage current. Here, J is the current density, S is the electrode area, and d is the specimen's thickness.

$$J(t) = \frac{1}{S} \cdot I(t) = \frac{1}{S} \cdot \frac{dQ}{dt} \quad\cdots\cdots\cdots\cdots (4)$$

Also,

$$J_{cond} = \kappa \cdot E = \kappa \cdot \frac{V_{dc}}{d} \quad\cdots\cdots\cdots\cdots (5)$$

Therefore,

$$\kappa = \frac{d}{S} \cdot \frac{1}{V_{dc}} \cdot \frac{dQ}{dt} \quad\cdots\cdots\cdots\cdots (6)$$

These physical property values can be calculated by a single measurement. More general information about the dielectric characteristics of a material can be obtained by calculating the electric field dependence and temperature dependence while the applied field and measurement temperature are changed.

3. Experimental

3-1 Equipment

A Q(t) meter (AD-9831) manufactured by A&D Company, Ltd. and a DC power source (HMBR-30R0.4, max: 30 kV, 0.4 mA) manufactured by Matsusada Precision Inc. were used in the experiment.

The experiment procedure is as follows. First, measurement using a Q(t) meter was conducted through the entire process from the commencement of electric charge to short-circuiting of the measurement system. This made it possible to evaluate not only the steady state but also the electric current behavior in transient phenomena during charging and discharging.

A charging voltage was applied from the low electric field side at eight stages between 2.5 and 100 kV/mm. The specimen was set to the measurement system shown in Fig. 2.

A Rogowski type electrode was used on the high-voltage side, and a double electrode system consisting of measuring electrode and guard electrode was used on the low-voltage side. The effective diameter of the measuring
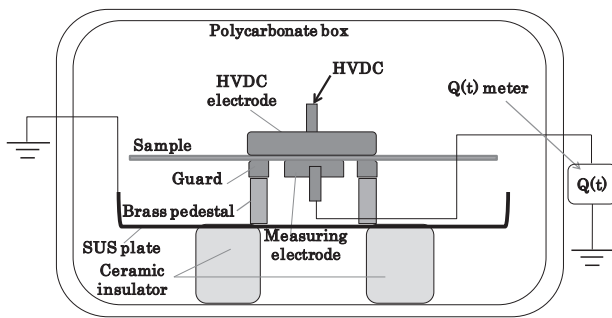
Fig. 2. Overview of testing electrode

electrode was 65 mm.

Voltage was applied by turning on S1 in Fig. 1(a). The boost time up to the designated voltage V_{dc} was two seconds, and V_{dc} was retained for 600 s. Next, S_1 was turned off and S_2 was turned on, and voltage application was stopped to perform self-discharging for 300 s. Subsequently, S_2 and S_3 were turned on to short-circuit the Q(t) meter and finish the measurement. This operation caused Q(t) to return to 0. To change the applied voltage, voltage was applied repeatedly in this condition. The measurement was conducted at room temperature and 80°C.

3-2 Specimens

Low density polyethylene (LDPE), high density polyethylene (HDPE), and polystyrene (PS) were used as specimens.

For LDPE and HDPE, additive-free commercially available grades were selected. The material was homogenized in a roller mixer at 140–160°C without mixing additives, and was pressed to fabricate sheets of 0.2 mm thickness.

For PS, commercially available sheets of 0.2 mm thickness were used.

Table 1 shows the chemical structure and dynamic viscoelasticity measured in oscillation mode (10 Hz at 25°C) as a typical physical property of respective materials. E_r is the storage modulus, E_i is the loss modulus, and tanδ is the ratio.

E_r of LDPE is smaller than that of HDPE or PS. This indicates that LDPE is more flexible than other materials.

Table 1. Chemical structure and viscoelasticity of respective materials

	Chemical structure	Viscoelasticity (25°C, 10 Hz)		
		E_r [Pa]	E_i [Pa]	tan δ
LDPE	$-(CH_2\text{-}CH_2)_n-$	4.0×10^8	4.7×10^7	0.12
HDPE		1.9×10^9	9.1×10^7	0.047
PS	$-(CH_2\text{-}CH)_n-$ ⬡	3.3×10^9	5.9×10^7	0.018

4. Measurement Results

Figure 3 shows the Q(t) curve of each material measured at room temperature and 80°C. The scale of the vertical axis is standardized to ensure easy comparison.

As Fig. 3 indicates, the characteristics of the three types of materials are significantly different. Both LDPE and HDPE are categorized as polyethylene and their basic chemical structure is the same, but their behavior is considerably different.

Namely, the time change of Q(t) of LDPE increased at over 20 kV/mm (gradient increased) even at room temperature. In the case of HDPE, a similar trend was not observed at normal temperature.
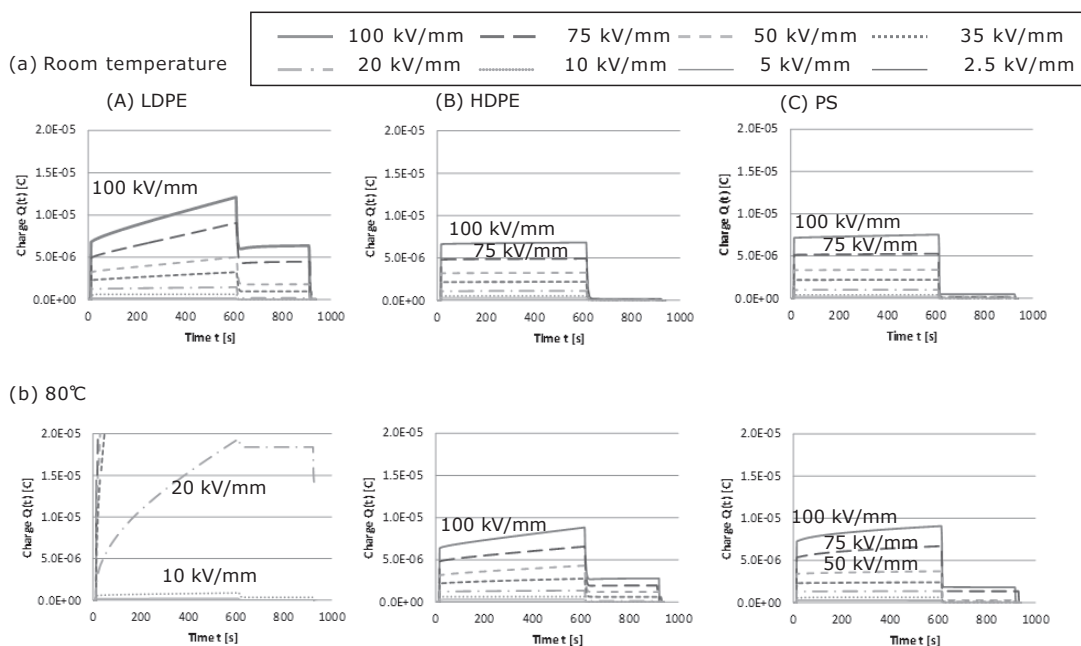

Fig. 3. Q(t) curve of respective specimens ((a)room temperature, (b) 80°C)

At 80°C, the Q(t) gradient of LDPE further increased, but the change for HDPE was small. Regarding PS, which contains aromatic rings in its molecules, Q(t) changed slightly in the high electric field at 80°C, but the difference attributed to the temperature and electric field is considered to be small.

5. Discussions

5-1 Permittivity and electrical conductivity

We used the data to calculate relative permittivity (ε_r) and electrical conductivity (κ) when 100 kV/mm was applied based on the method described in Section 2. The results are shown in Table 2. The ε_r value of LDPE is extremely high at 80°C presumably because Q_0 contains components of so-called space charge polarization attributed to charge transfer.

Table 2. Relative permittivity and electrical conductivity of respective materials (100 kV/mm applied)

		Relative permittivity ε_r	Electrical conductivity κ [S/m]
LDPE	RT	2.29	2.41×10^{-14}
	80°C	4.91	2.09×10^{-12}
HDPE	RT	2.24	7.29×10^{-16}
	80°C	2.16	1.09×10^{-14}
PS	RT	2.44	1.79×10^{-17}
	80°C	2.50	6.15×10^{-15}

5-2 Space charge accumulation behavior

The electric field dependence of the charge ratio Q_{300}/Q_0 (i.e. ratio between Q_{300} [Q(t) when t = 300 s] and Q_0) is indicated in Fig. 4. The data at room temperature are presented in (A), and the data at 80°C are presented in (B). The graph on the left side shows the overall image, and the graph on the right side shows an enlarged view of vertical axis near 1 (0.8–1.6).

At room temperature, the charge ratio of LDPE increased in the high electric field. This is considered to reflect the space charge accumulation.[4] For HDPE and PS, the charge ratio remained almost unchanged at around 1. This indicates that the charge accumulation of HDPE and PS is extremely low at this temperature and in this electric field. The dependence of the charge ratio on the applied electric field can also be identified. In the case of LDPE, charge injection starts at over 10 kV/mm and accumulation increases, though the amount is small.

At 80°C, the charge ratio of LDPE increased significantly in line with the increase of the electric field. When the charge ratio exceeded 2, conduction became dominant. Under this condition, conduction (not charge accumulation) occurred significantly in LDPE. The charge ratio of HDPE and PS was stable compared to that of LDPE.

When the area that the charge ratio is near 1 is enlarged, it becomes obvious that PS's charge ratio is smaller and the startup electric field is higher than that of HDPE (see the graph on the right side of Fig. 4 (B)). This difference is attributable to the difference in the electric field which the charge injection is occurred at. According to the graph, it is estimated that the charge injection occurs at 20 kV/mm or higher for HDPE and 50 kV/mm or higher for PS. It should be noted that PS has aromatic rings in each monomer unit in its molecules, and this is believed to inhibit charge accumulation and conduction.[5]
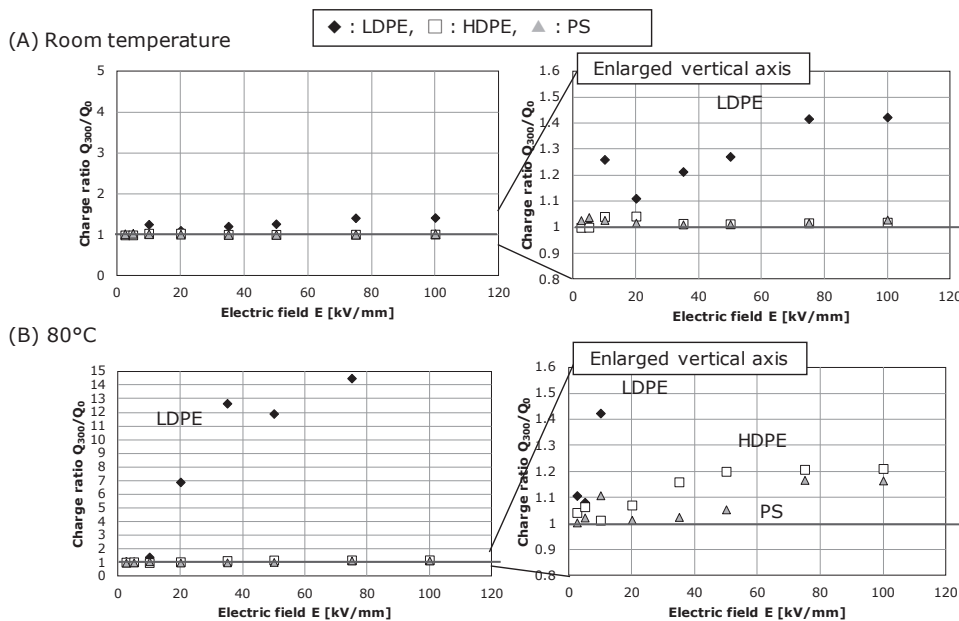

Fig. 4. Electric field dependence of charge ratio Q_{300}/Q_0

6. Conclusion

We evaluated Q(t) of LDPE, HDPE, and PS using the DCIC-Q(t) method. Eight levels of applied voltage were set between 2.5 and 100 kV/mm. To conduct the analysis, all the electric current components were factored in from immediately before voltage application to short-circuiting of the Q(t) meter under respective conditions.

The difference between materials was minimal in the low electric field. At over 10 kV/mm, LDPE showed an increase in Q(t) even at room temperature (an increase in gradient against time). The trend became more significant at high temperature. Meanwhile, PS did not show significant increase in the Q(t) increase speed even at 100 kV/mm. The behavior of HDPE (polyethylene) was close to that of PS.

In this research, we analyzed the Q(t) data and evaluated permittivity, space charge accumulation behavior, and electrical conductivity. The DCIC-Q(t) method is a simple measurement technique that can be used to evaluate various dielectric and insulation characteristics. Thus, it is expected to be widely deployed to screen electrical insulating materials, measure status change, and make deterioration evaluations.

The DCIC-Q(t) method also makes it possible to conduct measurements of electrodes regardless of their shape, and is applicable to electric wires and cables, as well as semiconductor devices.

In terms of space charge measurement, this method can be used for measuring fast-moving charges (which was difficult using the conventional PEA method), thin specimens, and measurements at high temperature.

As shown in Table 3, the DCIC-Q(t) method is expected to enable supplementary and general evaluation of materials and phenomena in combination with conventional measurement techniques such as the PEA method and picoammetry.

Table 3 Characteristics of respective measurement techniques

	Picoammetry	DCIC-Q(t)	PEA
Space charge	×	×	◎
Charge amount	×	◎	○
Electrical conductivity	◎	◎	×
Permittivity	×	◎	×

◎ : well available, ○ : available, × : not available

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