# News From Japan

Yoshimichi Ohki

## Current Integration Method, a Revisited Innovative Tool for Measuring Insulation Behavior

In the News from Japan column in the March/April 2021 issue [1], a brief introduction of the Ninth International Symposium on Electrical Insulating Material (ISEIM) was described. It was also described that the $Q(t)$ method developed by Prof. Tatsuo Takada of Tokyo City University had been introduced in a seminar taking place in the Ninth ISEIM. As mentioned in that column, the principle of the $Q(t)$ method itself is well known. However, this revisited method is very innovative and truly useful. Regarding this, although a measurement example of the $Q(t)$ method was briefly introduced in the above March/April issue, more examples are being introduced in detail in this issue and the next issue.

In 1972 Prof. Takada charged sheets of polyethylene terephthalate (PET) and low-density polyethylene (LDPE) electrostatically by applying a high voltage of the positive or negative polarity to a bundle of needle electrodes set above the sheet [2]. That is, the upper part of the sheet was positively or negatively charged as a result of the deposition of positive or negative ions flowed from glow discharges generated at the electrode tips. During the charging process, a capacitor installed between the lower part of the sheet and the ground was charged to $Q_0$ by the current flowing through the sheet. As shown in Figure 1, which is Figure 6 in the above-mentioned News from Japan, Takada compared $Q_0$ with the product $C_sV_s$. Here, $C_s$ is the capacitance of the sample sheet and $V_s$ is the potential difference generated in the sheet. As a result, $Q_0$ stayed almost constant in PET after it had increased to a value almost equal to $C_sV_s$ as long as $V_s$ was not too high. This was observed regardless of whether the film was charged with positive ions or negative ions. However, in the case of LDPE, it was found that the value of $Q_0$ became much higher when the ions deposited on the sheet were negative than when they were positive and that $Q_0$ continued to increase over time. This result indicates that the electric charge carriers hardly move in the sample sheet in the case of PET, but they move in the LDPE sheet to induce a leakage or conduction current.

To obtain a clue to analyze the above phenomena, Prof. Takada estimated theoretically how the charge ratio, $\beta = Q_0/(C_sV_s)$, changed depending on the charge distribution in the film. The essentials of the results are redrawn in Figure 2 [2]. The top inset shows a fundamental case like a parallel plate capacitor where positive charge $+Q_0$ and negative charge $-Q_0$ are present only on the two electrodes, making a potential difference of $V_s$. In this case, $\beta = 1.0$.

On the other hand, if charge carriers of a single polarity are injected from the electrode with the same polarity as that of injected carriers, *b* becomes larger. Here, if the carriers are injected with a uniform density throughout the sample sheet, the electric field strength on the surface of the injecting electrode becomes null when β reaches 2.0. That is, with the same potential difference between the two electrodes, the maximum amount of charge that can be present inside the sample is twice the charge present only on the electrodes in the above-men-

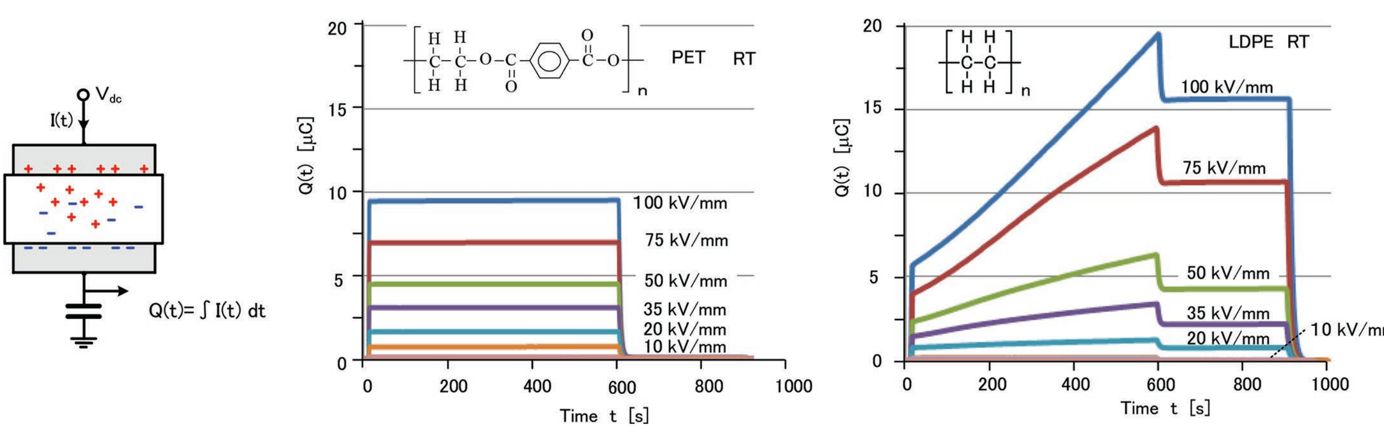



**Figure 1.** Comparison of the insulating properties between low-density polyethylene (LDPE) and poly(ethylene terephthalate) (PET); an example to show the versatility of the $Q(t)$ method. (Figure 6 in [1], reposted).

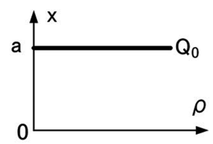
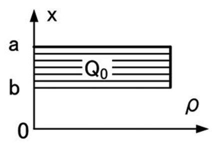
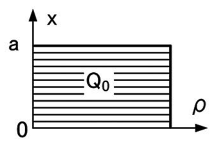
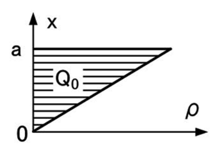
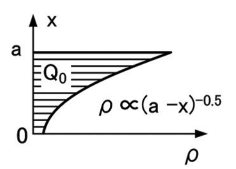
| Space charge distribution | Related formula | $Q_0 = \beta C_s V_s$ Charge ratio $\beta$ |
|---|---|---|
|  | $Q_0 = C_s V_s$ | 1 |
|  | $Q_0 = \frac{2a}{a+b} C_s V_s$ | $\frac{2a}{a+b}$ |
|  | $Q_0 = 2C_s V_s$ | 2 |
|  | $Q_0 = 1.5C_s V_s$ | 1.5 |
|  | $Q_0 = 1.5C_s V_s$ | 1.5 |



**Figure 2.** Effects of the charge distribution profile in a capacitor on the charge ratio β.

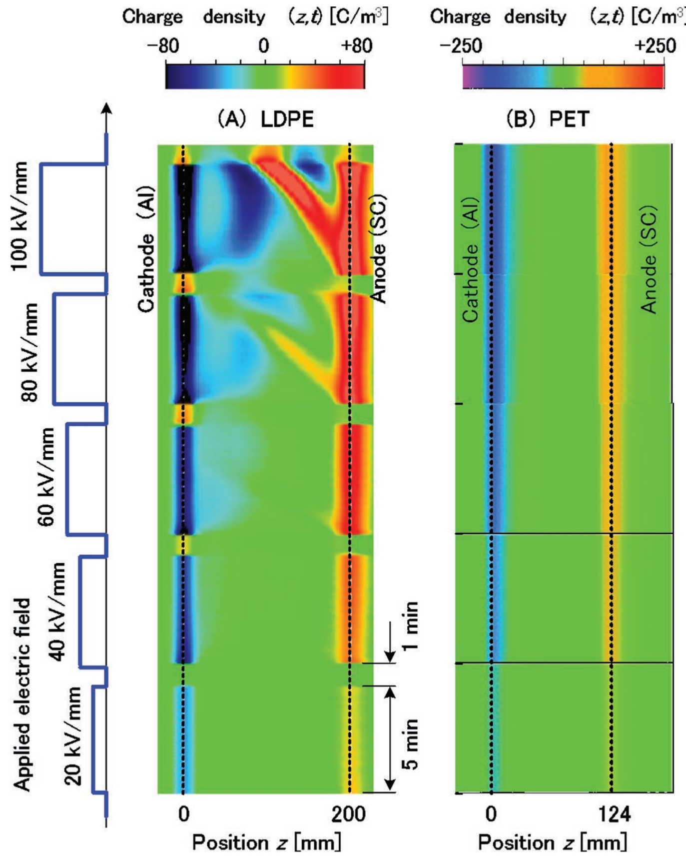



**Figure 3.** Space charge distributions in the sheets of low-density polyethylene (LDPE; A) and poly(ethylene terephthalate) (PET; B) measured by the pulsed electroacoustic (PEA) method.

tioned fundamental case. This situation is demonstrated in the third inset from the top in Figure 2.

If no extra-conduction currents flow, the total charge present in the sample system, including both on the electrode surfaces and inside the sample bulk, was transported via the current flowing through the sample. This in turn means that it is possible to know whether space charge is accumulated in the sample sheet if the current flowing through the sheet is integrated in a capacitor connected in series for acquiring the amount of electric charge or the value of β.

Since this paper [2] was published in Japanese, various pieces of discussion occurred mainly in Japan. To be honest, there were many critical reactions at that time. First, it is easy to see that a large conduction current flows without forming any space charge when the insulation of the sample is not good. For this reason, even if the amount of charge integrated in a series-connected capacitor increases more than the product of the capacitance of a solid dielectric and the voltage across it, this does not necessarily indicate the presence of space charge in the solid dielectric. In other words, [2] was criticized that the accumulation of space charge could not be estimated by this method.

In response to and encouraged by such criticism, Professor Takada made great efforts to measure the distribution of space charge in a dielectric solid. As a result, the pulsed electroacoustic (PEA) method was developed. Because the PEA method is widely used around the world, and many papers have published measurement results acquired using the method, elaboration on this will not be done here.

In recent years, DC power cables have been developed and operated for various purposes such as off-shore wind-power generation and power interconnection across straits. Therefore, the importance of measuring the space charge has increased more than ever. In particular, in the case of DC, it is more important to know the presence of leakage or conduction current and the accumulation behavior of space charge while applying the voltage than in the case of AC. Because the $Q(t)$ method is, in principle, a measurement while applying a voltage, Takada thought that this current integration method, which had been developed by him in the 1970s, should be released again. Therefore, this method was re-debuted with the easy-to-understand name of the $Q(t)$ method. As a typical and good example of measurement by the $Q(t)$ method, a comparison of electrical insulating behavior between LDPE and PET was conducted again using sheet samples supplied recently, as mentioned in this column of a previous issue [1] (Figure 1).

As mentioned above, the $Q(t)$ method integrates the electric current flowing in a sample. Therefore, all kinds of current equally contribute to $Q(t)$, regardless of whether it is conduc-

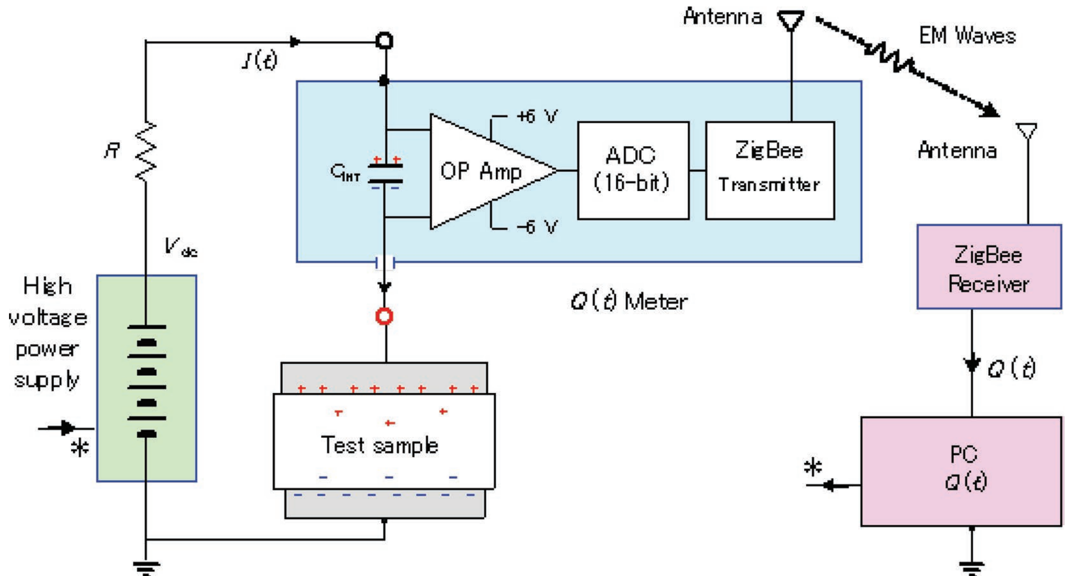



**Figure 4.** Schematic diagram showing the principle of the $Q(t)$ meter suitable for remote measurement.

tion current or due to the formation process of space charge or dipolar orientation or caused by partial discharges. In this regard, it is desirable to apply the $Q(t)$ method in combination with a method that can measure the space charge distribution, such as the PEA method. Figure 3 shows the PEA measurement data measured in such a way at the same time as the measurement of $Q(t)$, taking the data related to Figure 1 as an example.

In the case of LDPE shown in Figure 1, β eventually exceeds 2.0. This demonstrates that at least not only the space charge but also the conduction current should be responsible for this $Q(t)$ behavior because β cannot exceed 2.0 if no conduction currents are flowing. That is, assuming that the current $I(t)$ is composed of the instantaneous displacement current $I_d(t)$, delayed absorption current $I_a(t)$, and conduction current $I_c(t)$, $Q(t)$ becomes

$$\begin{aligned} Q(t) &= \int_0^t \{I_d(t) + I_a(t) + I_c(t)\}\,\mathrm{d}t \\ &= Q(t = +0) + Q_a(t) + Q_c(t). \end{aligned} \tag{1}$$

Here, $Q_a(t)$ and $Q_c(t)$ are components of $Q(t)$ associated with the integration of $I_a(t)$ and $I_c(t)$, respectively. In addition, since $I_d(t)$ flows only in a very short time, its component of $Q(t)$ can be represented by $Q(t = +0)$.

Furthermore, if $I_c(t)$ in Equation (1) obeys the Ohmic rule, $I_c(t)$ becomes constant with time, taking a value determined by the conductivity of the sample and the electric field applied to it. Therefore, $Q_c(t)$ is simply proportional linearly to $t$ in such a case. Taking these into account, when we see Figure 1, we find that $Q(t)$ is mainly composed of $Q(t = +0)$ in PET and $Q(t = +0)$ and $Q_c(t)$ in LDPE because we hardly see their $Q_a(t)$ components that increase gradually and slowly with time.

Because the principle of the $Q(t)$ method is very simple, it seems not so difficult to make a device to measure $Q(t)$. Here, with the hope that the $Q(t)$ method becomes popular throughout the world as in the case of the PEA method, Prof. Takada developed a $Q(t)$ meter that can be used easily and inserted into either a high-voltage side or a low-voltage side of a measurement sample. Its principle is shown in Figure 4. With the help of an analog–digital converter and a ZigBee transmission unit with an antenna, data acquired experimentally are transported instantaneously to a PC set at a remote place [3]. This device, AD9832, shown in Figure 5, is sold by A&D Company Ltd., Tokyo. Other aspects of the $Q(t)$ method, focusing on its industrial applications, will be reported in this column of the next issue. The heating plate with a thermometer seen in Figure 5 makes it possible to examine the effect of the sample temperature on the sample's $Q(t)$ characteristics by doing experiments after the temperatures of the upper and the lower electrodes become equal.

This article was completed in cooperation with Dr. Tatsuo Takada, Professor Emeritus of Tokyo City University, and Yoitsu Sekiguchi of Sumitomo Electric Industries.

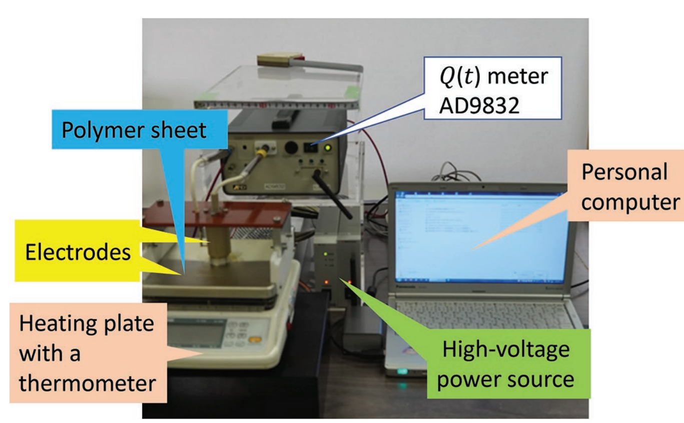



**Figure 5.** Scene of $Q(t)$ measurement.

## References

[1] Y. Ohki, "News from Japan—Ninth ISEIM held in Tokyo," *IEEE Electr. Insul. Mag*., Vol. 37, No. 2, pp. 40–43, 2021.

[2] T. Takada, T. Sakai, and Y. Toriyama, "Deduction of electric charge distribution in polymer film," *Trans. Inst. Electr. Eng. Japan*, Vol. 92-A, No. 12, pp. 537–544, 1972 (in Japanese).

[3] T. Takada, T. Tohmine, Y. Tanaka, and J. Li, "Space charge accumulation in double-layer dielectric systems—Measurement methods and quantum chemical calculations," *IEEE Electr. Insul. Mag*., Vol. 35, No. 5, pp. 36–46, 2019.