Studies on Location Technique of Corona and Measurement of Space Charge in Transformer Oil

By

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(Received June 28, 1983)

Abstract

An investigation has been made in order to develop the location technique of corona discharge in insulating oil, on behalf of the development of the UHV transformer. This paper describes the principle of analysing the corona location by making use of electrostatic probes. The corona produces a space charge in the oil, and induces charges on the probes electrostatically. Thus, the location as well as the space charge quantity of the corona can be analyzed, based on the induced charges of the probes. For this investigation, a needle-plane electrode and four probes were arranged in the oil, and a lightning impulse voltage was applied to the gap. Then, the corona produced in the gap was investigated by measuring the corona current and the induced charges on the probes, and then taking photographs of the corona. From these experiments, it was proved that this technique was quite useful for analyzing the location of the corona.

1. Introduction

In a large capacity power transformer, if the corona discharge occurs in the oil, the pressboard and the insulating oil which construct the transformer insulating system, are reduced in their insulation performance by the corona. So far many researchers have investigated the corona discharge phenomena in insulating oil. Recently, associated with an increase of the transmission line voltage, the insulation distance increases on the inside of the transformer. However, the transformer size is restricted severely, because of its transportation and installation space problems.

On the occasion of a design and test for a compact transformer, one of the most important problem is a corona discharge developed from the weak points, eg., edges of windings, so that the identification of the corona location has become necessary. Hitherto, the detection of the corona has been tried by means of acoustic emission etc., but it can not be performed practically.

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In this paper, the principle to identify the location of the space charge produced in the oil by a corona discharge is described, using the induced charge on the electrostatic probes arranged in the oil-tank. Based on the induced charges on the probes, the corona location as well as its space charge quantity can be analyzed. Furthermore, through the application of this method, the detection of the corona generated in a need-leplane gap in an oil-tank made of acryl, is performed. The effectiveness of this method is established in the results.

2. Principle of Corona Location and Measurement of its Charge Quantity

The space charge, generated by the corona in the oil-tank, is considered to be distributed along the path of the corona. However, if the volume of the corona space is small and is measured from a sufficient distance, the space charge can be regarded as a point charge. As shown in Fig. 1, a metal sphere with a radius a is arranged above the plane as a probe, and grounded to the earth. Let the charge of the point charge be Q_s, the charge induced electrostatically on the probe P be q', and the induced charge by $-Q_s$ (image charge of Q_s due to the plane electrode) be q'', as shown in the figure.

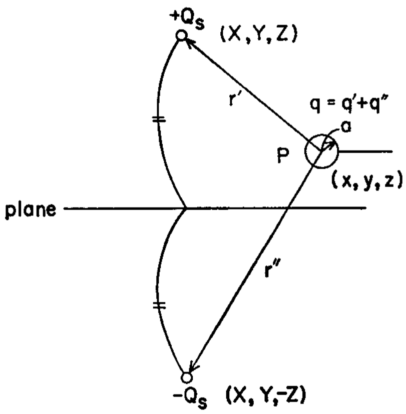


Fig. 1. Relation of the corona charge Q_s and the induced charge q on the probe P.

Then, the relationships between these charges are given as follows:

$$q=-(a/r')Q_s, \quad q=(a/r'')Q_s \tag{1}$$

$$q=q'+q'' \tag{2}$$

Hence,

$$q=(-a/r'+a/r'')Q_s \tag{3}$$

where, r', r'' represent the distance between P and Q_s, P and $-Q_s$ respectively.

Provided that Q_s is known, its location being (X, Y, Z) and that 3 probes $(P_i, i=1, 2, 3)$ are arranged around the charge, the following relations are held:

$$aQ_s\left\{\frac{1}{\sqrt{(X-x_i)^2+(Y-y_i)^2+(Z-z_i)^2}} - \frac{1}{\sqrt{(X-x_i)^2+(Y-y_i)^2+(Z+z_i)^2}}\right\}-q_i=0, \quad (i=1, 2, 3) \tag{4}$$

where (x_i, y_i, z_i) denote the coordinates of the center of the probe P_i.

When q_i's are measured and substituted into Eq. (4), these equations can be solved and the coordinate of Q_s can be found. In this paper, Brent's method has been utilized for numerical calculation.

Sometimes, Q_s in the transformer may not be measurable, and in such cases, there exist 4 unknown quantities. Hence, in order to find them, a fourth probe must be arranged, and the fourth equation with the same form as Eq. (4) is established as follows. Thus, the 4 unknown quantities can be solved numerically.

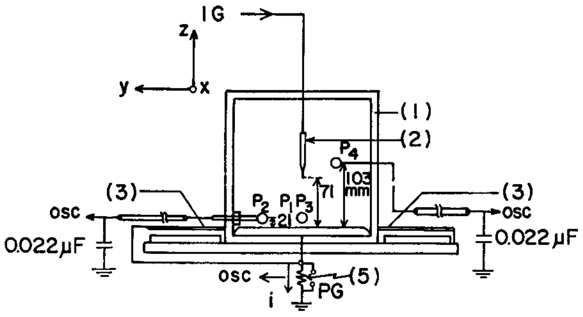
$$aQ_s\left\{\frac{1}{\sqrt{(X-x_i)^2+(Y-y_i)^2+(Z-z_i)^2}} - \frac{1}{\sqrt{(X-x_i)^2+(Y-y_i)^2+(Z+z_i)^2}}\right\}-q_i=0. \quad (i=1, 2, 3, 4) \tag{5}$$

Here, since the probes have been arranged together, the electric charges are induced mutually between them. In the experiment, however, the probes were separated far from each other, so that the mutual effects are ignored in this paper for simplicity.

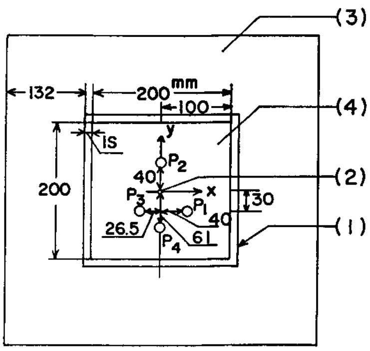
3. Experimental Apparatus and Method

3-1. Experimental method

The electrode arrangement which constructs the needle-plane gap is shown in Fig. 2. This needle-plane gap (gap length: 71 mm) is set in the oil-tank. The



(a) Side view



(b) Top view

Fig. 2. Experimental apparatus.

shape of the tank is cubic, made of acryl with a 20 cm side length. The oil used here is the JIS No. 2 in which $\varepsilon = 2.2$, $\rho_V = 10^{13}\ \Omega$cm, and is of ca. 8 *l*. . A needle (No. 2 for cotton cloth on the market) was used as the point electrode, and was sharpened making the point at an angle 30°, and the curvature at 0.3 mm. The plane electrode has a rectangular form with a 20 cm side length, and was set in the inside bottom of the tank. Because the plane electrode is too small to be regarded as an infinitely large plane, an auxiliary electrode is arranged outside the tank, as shown in Fig. 2.

Each of the four electrostatic probes ($P_1 - P_4$) for measuring space charge quantity and its location had a 5 mm radius, and was arranged at a different height above the plane and at a different distance from the electrode axis respectively. They all were grounded through capacitor C with 20000 pF. Provided that the center of the plane electrode is the origin, the coordinate of each probe (center) is shown in Table 1. The applied impulse voltages to the gap have the form of $\pm 1.4/74$ (μs). When the voltage was of a 50 kV peak, the corona stretched itself ca. 10 mm.

Table 1. Location of the probes

	x-axis (mm)	*y*-axis (mm)	*z*-axis (mm)
P_1	40	−30	21
P_2	0	40	21
P_3	−26.5	−30	21
P_4	0	−61	103

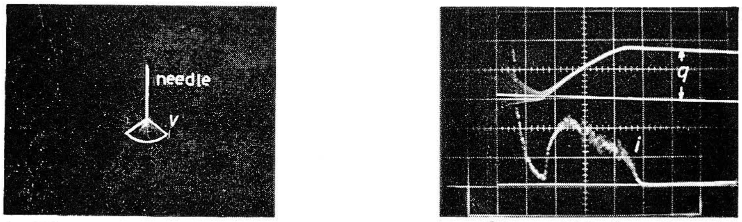
Note, *x*-, *y*-axis; horizontal plane, *z*-axis; vertical (gap)-axis.

The charge quantities $q_1 - q_4$ induced on the probes due to the corona were obtained through the terminal voltage of the capacitor, where two 2-beam oscilloscopes (TEK 7844, 556) were utilized for the voltage measurement. The induced charge on the probe depends not only on the corona charge Q_s, but also on the applied voltage to the needle electrode. In this experiment, however, the component due to the applied voltage was canceled by the use of a differential amplifier set in the oscilloscopes, and only the component due to the corona charge could be measured.

The space charge quantity produced by the corona can also be obtained by the time integration of the current flowing from the plane to the earth through the resistance R (10 Ω), where R is used to measure the current of the plane i, as shown in Fig. 2. Here, the time integrated value ($\int i\,dt$) is denoted by Q. However in general, Q is an apparent value, and is a little different from the true corona charge Q_s. Under the condition that the gap distance is much larger than the plane-electrode diameter, the relation between Q_s and Q is held generally as follows:

$$Q=\int i\,\mathrm{dt}<Q_s \tag{6}$$

In this experiment, however, the gap length is relatively small compared with the size of the plane electrode, and the needle electrode is sufficiently fine, so that Q can be regarded as equal to Q_s. Then;



(a) Photograph of the corona (v; Average corona region)
(b) q (0.43 nC/div.), i (2 mA/div.) (2 μs/div.)

Fig. 3. A example of measurement on the current of the plane i, the induced charge on the probe q and the photograph associated with the corona in the insulation oil (Applied voltage; +50 kV).

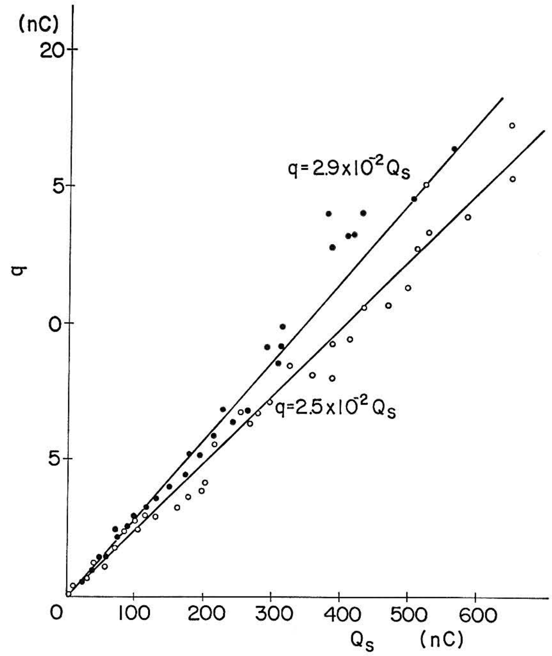


Fig. 4. Relations between amount of space charge Q_s and the induced charge on the probe (g=100 mm, ●; positive corona, ○; negative corona).

$$Q_s = Q = \int i \, dt \tag{7}$$

For the observation of the form of the corona with a high sensitivity, an image-intensifier was utilized along with a still camera. The photograph and the oscillograms of q and i associated with the corona, which were obtained by the experiment as described above, are shown in Fig. 3. The relation between Q_s and q for the positive and the negative corona respectively is shown in Fig. 4, where the positive and the negative voltage was applied to the gap respectively, changing its peak value.

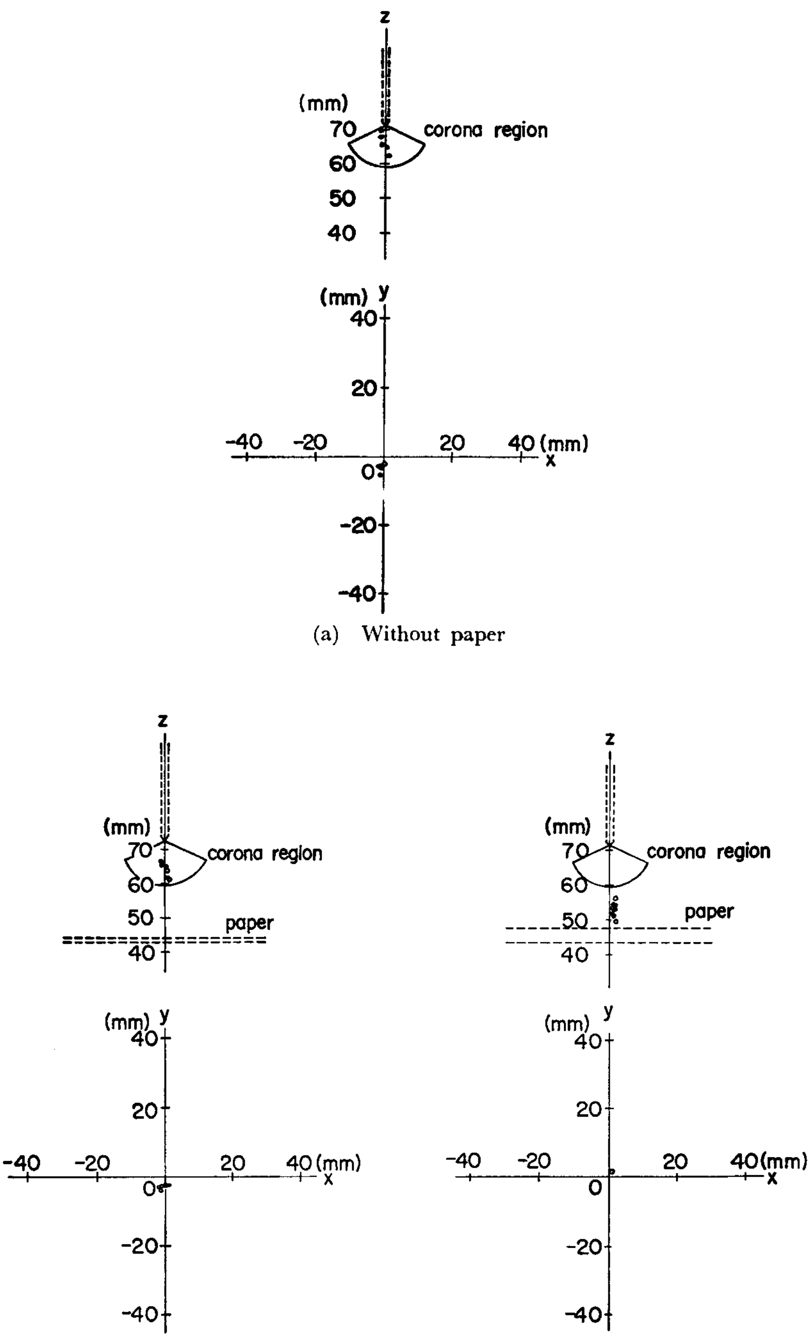
3-2. Experimental results

For the needle electrode described above, a positive impulse voltage (50 kV) was applied to produce the corona in oil. The induced charge (q_i) on each probe (P_i) was measured, and at the same time the corona form was observed. From the obtained data, the location and the charge quantity of the corona were calculated by Eqs. (4), (5). They were compared with the form taken by the still camera and the Q_s obtained by the current method (Eq. (7)). The experiment was also executed under the condition that a craft paper with a 0.65 mm or 4.0 mm thickness was inserted at 30 mm level under the needle tip, where the craft papers were stuck together by synthetic-rubber glue in order to get the necessary thickness.

Case a. Q_s known: By measuring the induced charges ($q_1 - q_3$) and Q_s (due to Eq. (7)) and substituting these values into Eq. (4), the equation has been solved simultaneously in order to obtain the corona location as shown in Fig. 5. The corona region is depicted in this figure, based on the picture taken by the still camera. The coronal location obtained by the calculation described above is shown by the marks (○), which have been obtained by applying impulse voltage five times to the oil gap. These five marks are contained in the corona region of this figure, and it is deduced that the locating method executed here is effective.

The corona locating method described above was applicable also where craft paper was inserted between the electrodes, and the experimental results are shown in Fig. 5(b), (c). These two graphs correspond to 0.65 mm and 4.0 mm in thickness of paper respectively. From Fig. 5(c), it can be seen that the corona region taken by the still camera does not include the charge location. Therefore, the locating method is not applicable in a case where there is thick paper between the electrodes. It may come from the reason that the difference between the dielectric constants of the oil and the paper is ignored in Eq. (4).

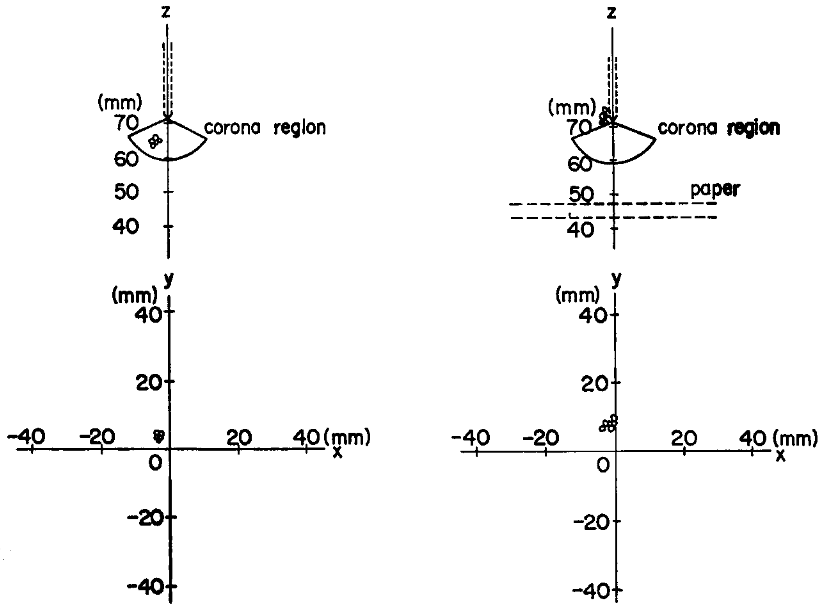
Case b. Q_s unknown: By measuring the induced charge ($q_1 - q_4$), and substituting these values into Eq. (5), the location (X, Y, Z) and the space charge quantity (Q_s) can be obtained by solving simultaneous equations. The result



(a) Without paper

(b) With paper of 0.6 mm thickness (c) With paper of 4 mm thickness

Fig. 5. Position of the corona charge evaluated by using Eq. (4) (Applied voltage; +50 kV).



(a) Without paper (b) With paper of 4 mm thickness

Fig. 6. Position of the corona charge evaluated by using Eq. (5) (Applied voltage; +50 kV).

is shown with good accuracy, as shown in Fig. 6(a), where only the probe P_4 was set at a higher level than the needle tip. If all probes are set in level lower than the needle tip, the calculated location of the corona will be obtained outside the corona region, as mentioned later. The space charge quantity produced by the corona was obtained as 47.7 ~50.3 nC by the probe method, and as 49.0 ~51.2 nC by the current method (Eq. (7)). Therefore, both values obtained by the two methods approximately coincide with each other, and this probe method seems effective for charge measurement.

In the case where the papers are inserted between the electrodes, the measurement results are shown in Fig. 6(b), where the paper is 4 mm in thickness, and the corona location has been obtained in close vicinity to the needle tip i.e. the corona region. Then, this locating method seems to be effective also where the paper exists, and the paper is thick. From these results, it is deduced that the method utilizing the electrostatic probes is effective for locating the corona discharge and for measuring the space charge quantity.

4. Consideration on Probe Arrangement and Measuring Sensitivity of Corona Location

The variation of the induced electric charge q_i on the probes were calculated for a point charge Q_s (=1 C) using Eq. (3). The results are shown in Fig. 7(a), (b), (c), where the location of the point charge is moved along the x-, y-, z-axis respectively. For example, when Q_s is moved along the x-axis as shown in Fig. 7(a), the curves of q_1 and q_3 intersect each other, since the distance between P_1 and Q_s, or between P_3 and Q_s, increases or decreases oppositely to each other, where P_1 and P_3 are arranged facing each other along the x-axis. On the contrary, since the distances between P_2 and Q_s, and between P_4 and Q_s change in same manner according to the change in x, the curves of q_2 and q_4 run parallel to each other.

Let the angle made by curves q_1 and q_3 be θ_x. Then, the sensitivity of the probe,

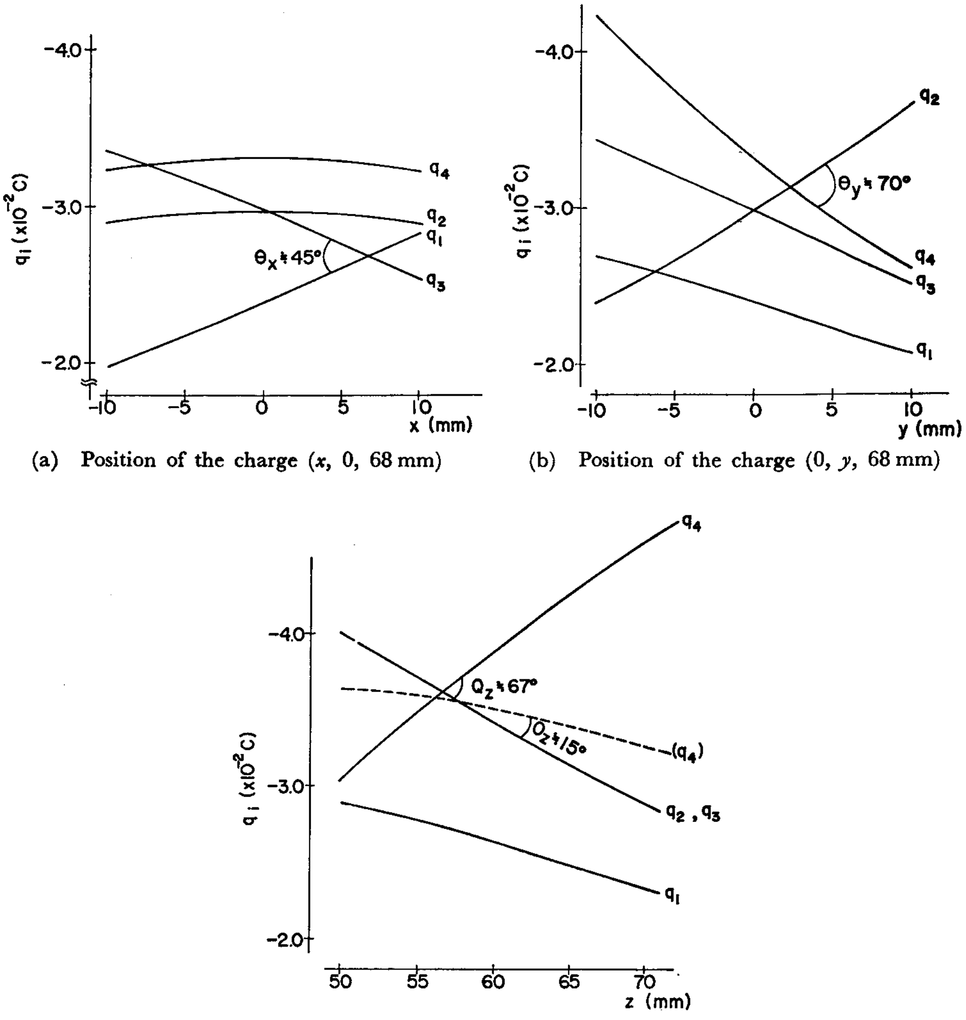


Fig. 7. Variation of q_i with the position of a point charge Q_s (=1 C).

against the change of the Q_s location along the x-axis, increases with an increase in θ_x. From the curves in Fig. 7, it is obtained that $\theta_x \fallingdotseq 45°$, $\theta_y \fallingdotseq 75°$ and $\theta_z \fallingdotseq 67°$. It is deduced from the experimental results mentioned earlier, that these angles are sufficient for analyzing the location of Q_s. When z_4 (coordinate of probe P_4) is changed from 103 mm to 35 mm (cf. Table. 1), the curve q_4 is shown by the broken line in Fig. 7(c), then θ_z is obtained as 15°. These experimental results of the corona location are shown in Fig. 8, where the corona location on the x- and y- axis is exactly performed, but not on the z-axis.

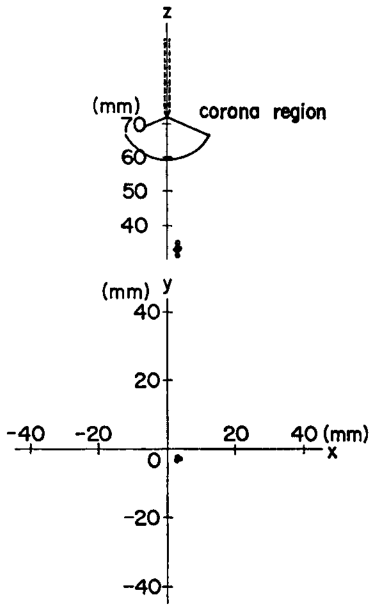


Fig. 8. Evaluated position of the corona charge with the probe P_4 located at (0, −61, 35 mm).

From these results, it is deduced that the angles made by the 4 curves of (q_1, q_3), (q_2, q_4) and (q_3, q_4) are preferably more than 45°, refering to θ_x in Fig. 7(a).

5. Conclusion

In this paper, the measuring method of space charge quantities and its location in the oil-tank has been described, based on the induced charge quantities on the probes arranged around the electrodes. The results have been obtained as follows;

1) In case the space charge quantity due to the corona is known, the corona location and its quantity can be measured by using induced charge quantities on the 3 probes arranged in the tank.

2) In case the space charge quantity is unknown, they, also, can be measured by 4

probes in the same manner as described above.

3) Consideration of the sensitivity of the probes due to their arrangement was carried out, based on the calculating results regarding the induced charge on each probe, and an effective arrangement has been determined.

Acknowledgment

The authors are thankful for the contributions to this experiment given by Mr. Shigeyoshi Ishitoku and Mr. Yukihiko Shimono, students of Kyoto University, and also for useful discussions and support given by Mr. Shoji Hirabayashi and Mr. Tsutomu Tani, Mitsubishi Electric Co..

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