Investigation of Charge Behavior in Low Viscosity Silicone Liquid by Kerr Electro-optic Field Measurement

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ABSTRACT

From the viewpoints of less flammability and environment protection, a new type of electrical insulating liquid for power transformers is strongly required. Low viscosity silicone liquid (20 cSt) is suitable for the requirements owing to the following excellent features; high flash point, low environmental impact concerning pollution and high chemical stability. In this paper, we investigated the charge behavior under dc voltage application by direct measurement of the electric field using Kerr electro-optic method. At first, Kerr constant of 20 cSt silicone liquid was investigated. Then, the time dependence of electric field strength in silicone liquid / pressboard (PB) composite systems was measured. The time constant of the decay was much larger in silicone liquid than in mineral oil. We discussed the charge behavior based on the physical properties of silicone liquid and we suggested that the influence of negative charge injection from a negative electrode's surface in silicone liquid played a significant role because of the high volume resistivity.

Index Terms — **Low viscosity silicone liquid, Electric field, Charge, Kerr electro-optic measurement.**

1 INTRODUCTION

ALTHOUGH mineral oil has been used for a long time as insulating oil for large power transformers so far, the requirements of the oil are not only the dielectric performance but also low environmental pollution. Thus, the development of the new type of the insulating oil for power transformers is strongly required [1-2]. Silicone liquid has high flash and fire points, high permittivity, low environmental pollution and high chemical stability. Its application to power transformers has been investigated [3-4]. In particular, low viscosity silicone liquid (20 cSt) has excellent cooling performance as well as good dielectric and insulation properties. To enhance the reliability and apply to large power transformers, the charge behavior in both liquid gaps and liquid / solid composite insulation systems must be clarified under various voltage conditions [5-6], as well as the fundamental insulation

properties and long-term aging characteristics of fluids [7-9].

For the electric field measurement, Kerr electro-optic field measurement technique is a powerful tool, because the technique can measure the electric field without any disturbances of the field distribution itself [10-11]. The authors used this technique for the field measurement in various liquid insulation systems so far [6, 12-14].

2 EXPERIMENTAL SETUP AND PROCEDURE

2.1 FIELD MEASUREMENT USING KERR ELECTRO-OPTIC METHOD

Figure 1 shows the experimental setup and the electric field measurement system using Kerr electro-optic method. A circularly polarized He-Ne laser beam passes through the electrically stressed oil in the test cell. By Kerr effect, a phase shift $\Delta\theta$ occurs between the beam components, which are
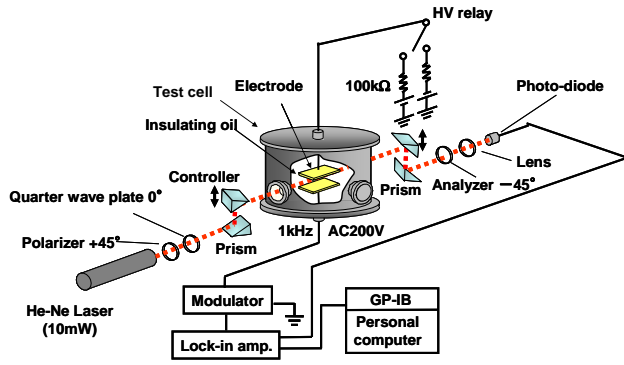
Figure 1. Experimental setup for electric field measurement in insulating liquid using Kerr electro-optic method.

Table 1. Properties of insulating liquid.

	Silicone liquid (20cSt)	Mineral oil
Specific gravity (g/cm^3) at 15°C	0.96	0.87
Kinematic viscosity (mm^2/sec) at 40°C	15	8.36
Flash point (°C)	264	145
Relative permittivity at 80°C	2.7	2.2
Volume resistivity (Ω·cm) at 80°C	9.5×10^{15}	4.6×10^{14}

parallel and perpendicular to the field vector. It is possible to know the electric field strength E from the value $\Delta\theta$ because the value $\Delta\theta$ is proportional to the square of field strength E. The electric field distribution was measured at many points by shifting the optical path.

All experiments were carried out at room temperature (15-25 °C) and moisture in the insulation liquid was kept at 10-20 ppm. The test vessel was filled with 20 cSt silicone liquid or mineral oil. Properties of insulating liquids are shown in Table 1.

2.2 ELECTRODE CONFIGURATION

Four kinds of PB insulation systems were examined as shown in Figure 2; a. parallel plane electrodes gap without PB (oil alone), b. PB on a grounded electrode, c. PB on both electrodes and d. PB at the center of the oil gap. Gap length was 10 mm and dc voltage was applied. Kerr constant of 20 cSt silicone liquid was identified by measuring the light intensity ratio at the mid gap (y=5 mm, Figure 2a) under the applied voltages from –15 kV to +15 kV. The electric field distribution along the gap was also measured.

Time dependence of the electric field strength was measured at four insulation systems shown in Figure 2, and their characteristics were compared and analyzed. The spatial field distribution was also measured in the parallel plane electrode (Figure 2a). In Figure 2b, PB or PMMA was placed on the grounded electrode, and temporal change of the electric field strength at position y=3 mm in the liquid gap was compared between PB and PMMA.

In Figure 2c, 0.8 mm thick PB was placed on both high voltage and grounded electrodes. Temporal change of electric field strength at position y=3 mm was measured at dc voltages of ±10 kV.
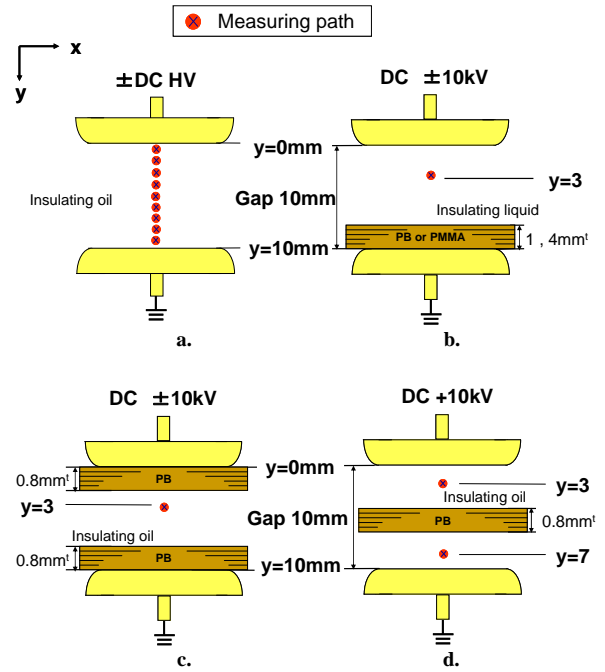

Figure 2. Insulation systems. **a**.Oil gap **b**. PB on grounded electrode **c.** PB on both electrodes **d.** PB at the center of oil gap

In Figure 2d, 0.8 mm thick PB was placed at the center of the liquid gap. Temporal change of electric field strength at position y=3 mm was measured at dc voltages of ±10 kV.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 DETERMINATION OF KERR CONSTANT OF LOW VISCOSITY SILICONE LIQUID

The relationship between light intensity ratio $I_{1\omega}/I_{dc}$ and applied field strength E_{dc} is expressed by the following equation (1) [10].

$$I_{1\omega}/I_{dc} = 4\pi BLE_{dc}E_{ac} \qquad (1)$$

where $I_{1\omega}$ is light intensity (first harmonic), I_{dc} is light intensity (dc), B is Kerr constant, L is the electrode length and E_{ac} is the applied electric field (ac).

The measurement results of the light intensity ratio $I_{1\omega}/I_{dc}$ under voltage application from –15 kV to +15 kV in 20 cSt silicone liquid and mineral oil are shown in Figure 3. Light intensity ratio $I_{1\omega}/I_{dc}$ is proportional to the average applied field E_{dc} in both insulating liquids. By substituting the measurement results for (1), Kerr constant can be derived. Obtained Kerr constant was 7.59×10^{-16} m/V^2 for 20cSt silicone liquid and 2.25×10^{-15} m/V^2 for mineral oil.

3.2 ELECTRIC FIELD MEASUREMENT RESULTS

3.2.1 OIL GAP (WITHOUT PB)

A step voltage of +10 kV was applied for 200 s. And temporal change in the electric field strength was measured. The results are shown in Figure 4. Measurement
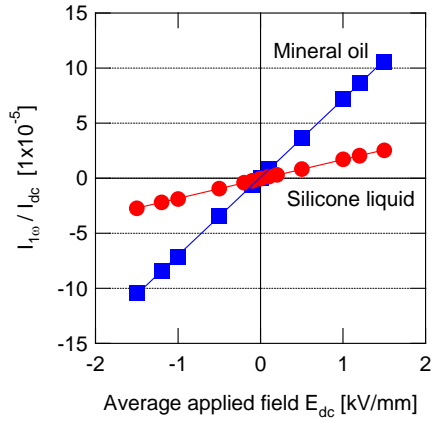
Figure 3. Relationship between light intensity ratio and applied field (mineral oil and silicone liquid).

characteristics were almost equal between both liquids. Moreover, the electric field responded rapidly to the instantaneous voltage at t=0 and 200 s.

The electric field distribution along oil gap is also measured in fresh mineral oil, aged mineral oil (volume resistivity of the deteriorated mineral oil was 10^{12} Ωcm at 25°C) and low viscosity silicone liquid. Figure 5 shows the measurement results of electric field distribution along oil gap at the steady state. The uniform field distribution was obtained for fresh mineral oil and silicone liquid. The results indicated no charge accumulation near the electrode surface. On the other hand, the enhancement of electric field closed to the cathode and anode electrode surfaces was obtained in the aged oil. The result indicated the hetero charge accumulation in aged oil.

3.2.2 PB ON GROUNDED ELECTRODE

When a solid insulator was placed on the grounded electrode, the electric field strength in silicone liquid was determined based on the relative permittivity of dielectric materials right after the voltage application, which then varied with time as shown in Figure 6. The insulator was PB or PMMA. Their thickness was set to 4.0 mm. Applied dc voltages were ±10 kV. Electric field in the liquid gap was measured at y=3 mm. When PB was inserted, the electric field strength at +10 kV was almost constant as shown in Figure 6a. However, it decreased with time at –10 kV.

When PMMA was inserted, the field strength decreased at both +10 kV and –10 kV. Decay of the field strength was larger at –10 kV than at +10 kV. This suggests that there are more negative charges than positive ones in the silicone liquid. The positive field strength decays with time in case of PMMA. On the other hand, the positive field strength little decays with time in case of PB. The reason why the different time dependence of electric field reduction appeared between PB and PMMA was not clear in this stage. For comparison of charge density between at +10 kV and at –10 kV, conductivity was calculated using the field strength in Figure 6b. In the silicone liquid, calculated conductivity at –10 kV is about 4.3 times larger than that at + 10 kV.

This relationship between conductivity and charge density is expressed by equation (2).
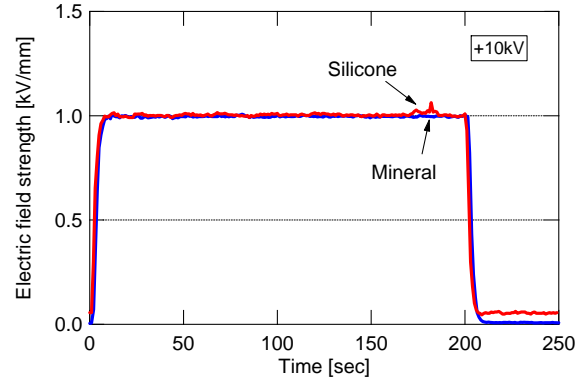

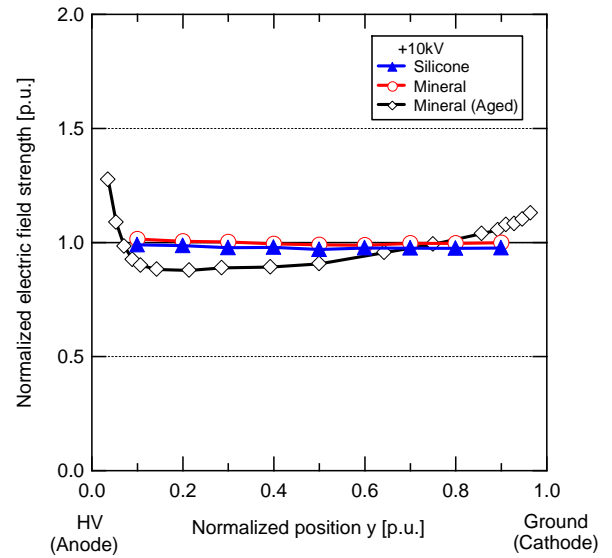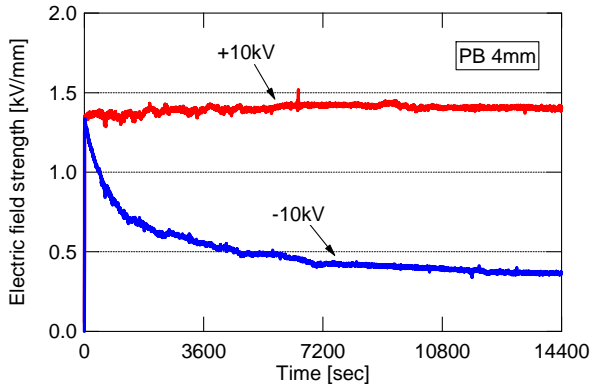**Figure 4.** Time dependence of electric field.

Figure 5. Electric field distribution along oil gap at the steady state.

$$\sigma = en\mu \tag{2}$$

Where σ is conductivity, e is electric charge, n is number density of charges and μ is mobility.

The silicone liquid is electrically neutral at the initial stage. So, it means that larger conductivity was caused in negative voltage application than in positive one.

Similar measurements were performed in mineral oil (applied dc voltage: ±10 kV, position y=3 mm). Results are shown in Figure 7. In mineral oil, electric field strength decreased with time at both voltage polarities, and the influence of charge injection was small because there were originally more charges in mineral oil than in the silicone liquid. In Figure 7a, decay of the field strength at –10 kV was larger than at +10 kV. There were many charges in the mineral oil, and charge accumulation on the PB / oil interface was faster at –10 kV than at +10 kV because of the ability of negative charge adsorption of PB [15]. In Figure 7b, decay of the electric field strength of both voltage polarities was almost equal. This means that PMMA has no negative charge adsorption ability.
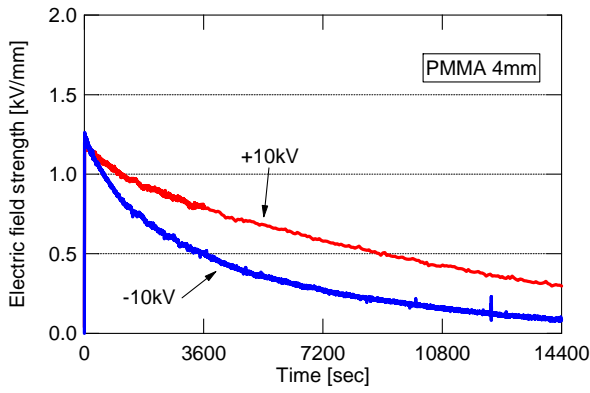
Figure 6. Time dependence of electric field in the silicone liquid/PB (PMMA) and configuration (PB and PMMA on grounded electrode). **a.** PB **b.** PMMA.

Charge density accumulated on PB at the steady state field is compared at −10 kV between both liquids in Figure 8. The accumulated charge density was estimated based on the following continuity relation (3) of dielectric flux density.

$$\varepsilon_{oil}E_{oil} + q_s = \varepsilon_{PB}E_{PB} \tag{3}$$

Where ε_{oil} and ε_{PB} are permittivity of oil and PB, E_{oil} and E_{PB} are electric field in oil and PB, and q_s is accumulated charge density.

Though the charge density on PB in mineral oil is larger than that in the silicone liquid, their discrepancy becomes small as PB becomes thicker.

3.2.3 PB ON BOTH ELECTRODES

Time dependence of electric field strength in the composite system in Figure 2c is shown in Figure 9. The field strength was measured at y=3 mm (insulation liquid gap) by applying ±10 kV. Electric field strength in mineral oil decreased with time. However, in the silicone liquid case, the field strength did not decrease with time. This phenomenon in the silicone liquid could be explained based on the difficulties of the negative charge injection from the negative electrode covered with PB. As the number of charges in the silicone liquid was
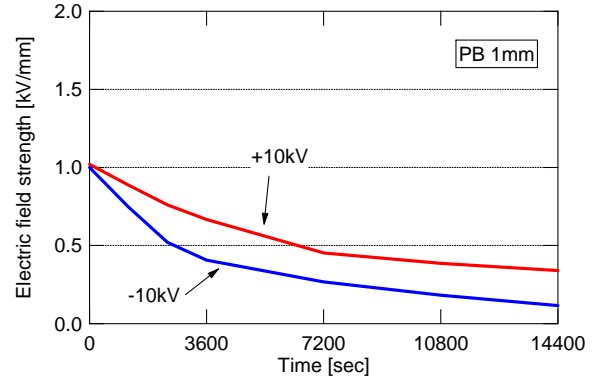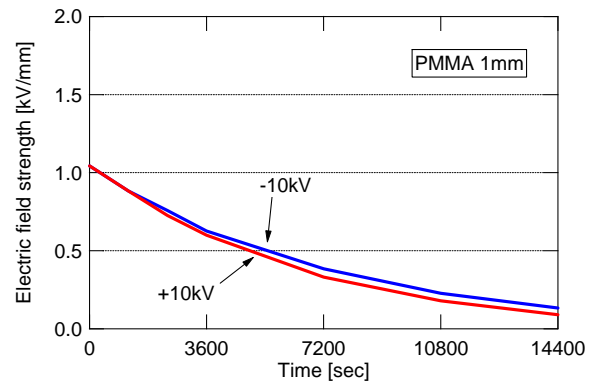
Figure 7. Time dependence of electric field in the mineral oil/PB (PMMA) and configuration (PB and PMMA on grounded electrode). **a.** PB **b.** PMMA.

very small, the time constant of charge accumulation on PB was larger than 14400 sec. Conversely, in case of mineral oil, as there were many charges, the field strength could decrease with time even if no charge is injected from the negative electrode.

3.2.4 PB AT THE CENTER OF OIL GAP

Figure 10 shows the time dependence of the field strength in the composite system in Figure 2d. Figure 10b has also the extrapolated plots obtained by the least square error estimation under the assumption that the measurement result after the peak of the electric field follows the exponential variation with time. The field strength was measured at y=3 mm and y=7 mm. The field strength at y=7 mm in mineral oil decreased with time (Figure 10a). This is caused by the negative charge accumulation on the lower side of PB. Conversely, field strength at y=3 mm increases first, and decreases after the peak.

This behavior could be explained by the charge accumulation on PB. As PB has the ability to adsorb negative charge, negative charge accumulates faster on the PB surface of the negative electrode side than on the surface of the positive electrode side. Therefore, the field strength at y=7 mm decreases with time. This decrease component is added to
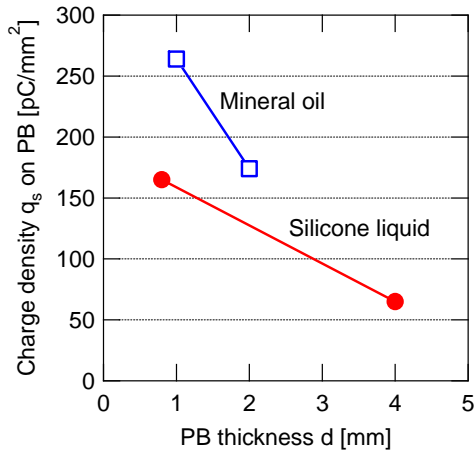
Figure 8. Charge density on PB of the silicone liquid and mineral oil.

Figure 9. Electric field strength in the silicone liquid and mineral oil in oil/PB on both electrodes.

a.

b.

Figure 10. Time dependence of electric field strength in the silicone liquid/PB and mineral oil/PB (PB at the center of oil gap). **a.** Mineral oil **b.** Silicone liquid

the field strength at $y=3$ mm, and the field strength at $y=3$ mm increases first. Positive charges are gradually accumulated on the PB surface in the positive electrode side, and then the field strength gradually decreases at $y=3$ mm. In case of the silicone liquid (Figure 10b), negative charges accumulate faster on the PB surface of the negative electrode side than on the surface of the positive electrode side because negative charges are injected from the negative electrode.

Based on the above measurement results and discussions, the potential distribution in Figure 2d could be estimated as curves in Figure 11. In the estimation, we used the equivalent circuit model consisting of resistance and capacitance in each material shown in Figure 11c. The potential is distributed according to the permittivity of the materials just after voltage application. Then the potential shares in the PB over time, but the number of charges is so small that time constant of charge accumulation is large. In contrast, in the mineral oil, similar potential behavior appears just after voltage application, and the potential shares in the PB over time. Although there are many factors affecting potential distribution; contaminations, moisture, impurities, etc, the difference in the time dependence of potential distribution between these two liquids is mainly caused by the difference in their volume resistivity, which is derived from the equivalent capacitive-resistive circuit model as shown in Figure 11.

Figure 12 shows the charge behavior in mineral oil and silicone liquid. The time dependence of electric field on the anode and cathode sides are different from each other. This was caused by the different speed of charge accumulation between charge polarities.

In both liquids, negative charge accumulates faster than positive one. However such difference between charge polarities seems to be caused by different mechanism. In the mineral oil, owing to the negative charge absorption on the PB surface, the negative charge accumulates faster than the positive one. On the other hand in silicone liquid, the negative charge accumulates faster because of the negative charge injection from the cathode electrode.
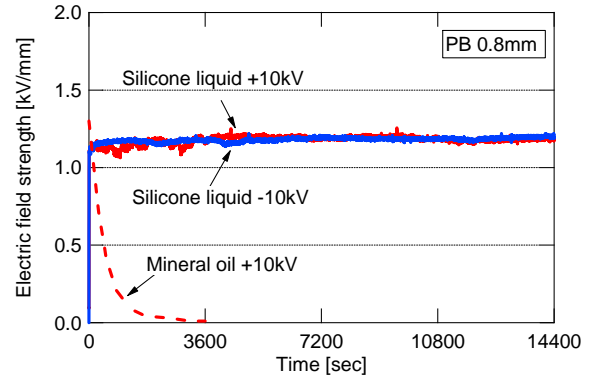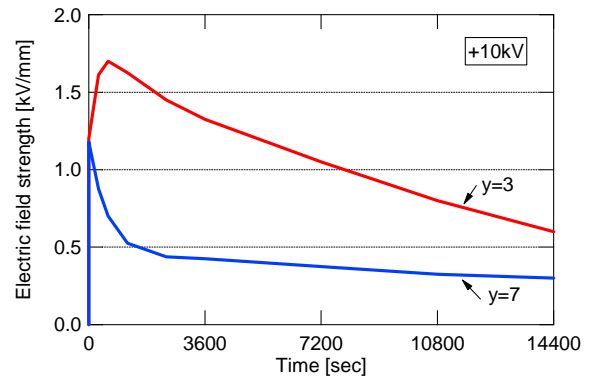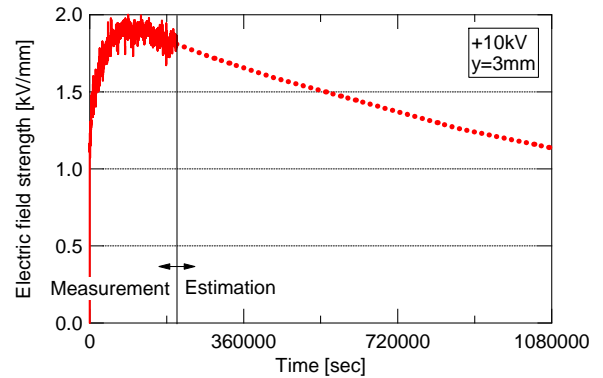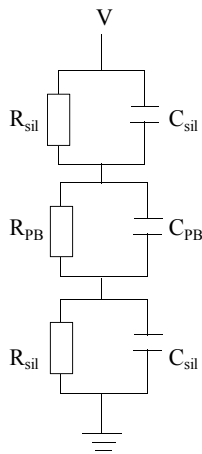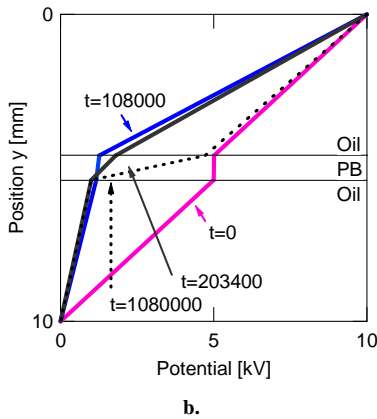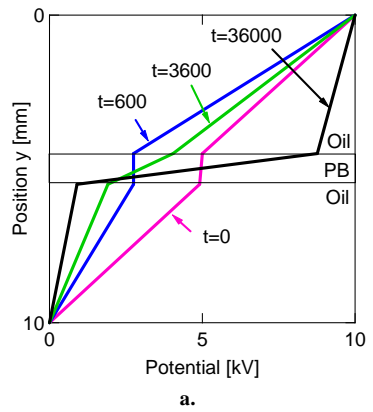
3.3 CHARGE IN SILICONE LIQUIDS

The experimental results are summarized as follows. In all PB arrangements, when the negative voltage is applied, the electric field in silicone liquid is decreased faster than positive one. There seem to be many reasons why such results were obtained; difference of ion mobility and the number of ions between polarities, impurities, electrode surface conditions, etc. Thus, in this stage, from the mechanism viewpoint, it is

Figure 11. Time transition of potential distribution in oil/PB configuration. **a.** Mineral oil **b.** Silicone liquid **c.** Equivalent circuit

R_{sil}, R_{PB}: Resistance of silicone liquid and PB layers

C_{sil}, C_{PB}: Capacitance of silicone liquid and PB layers

Figure 12. Charge behavior model in mineral oil/PB and silicone liquid/PB composite insulation systems. **a.** Mineral oil/PB **b.** Silicone liquid/PB

therefore, the field strength does not change and keeps at +10 kV during the measuring durations. Conversely, at −10 kV, negative charges were injected from the high voltage cathode electrode, drifted to PB and were adsorbed on the surface of PB. As a result, the field strength decreased with time. The possible mechanism of negative charge injection from metallic electrode to silicone liquid could be the difference of Fermi levels between them. Then, according to the references [16, 17], it would be possible to understand and finally the difference of field behavior between positive and negative voltage applications, can be explained.

4 CONCLUSION

Silicone liquid of 20 cSt viscosity has begun to be applied to power transformers. To realize optimum insulation performance, the behavior of electric field in fundamental insulation systems was measured and analyzed using Kerr electro-optic method. The following results were obtained.

(1) Kerr constant for 20cSt silicone liquid was 7.59×10^{-16} m/V^2 at room temperature. This value was one-third of the constant of mineral oil (2.25×10^{-15} m/V^2).

(2) In an insulating liquid / PB insulation system, electric field in both the silicone liquid and the mineral oil decreased with time except under such circumstances that a negative electrode was covered with PB in silicone liquid.

(3) The electric field in 20cSt silicone liquid was influenced by negative charge injection from a negative electrode, because only a few original charges exist in the silicone liquid owing to the higher volume resistivity. The electric field strength in the mineral oil, on the other hand, was determined by many charges existing in the oil from the initial stage.

hard to completely explain our results, however the electron injection from the cathode electrode would be one of the possible factors to determine the time dependence of the electric field. In silicone liquid, the number of charges is extremely small because of the higher volume resistivity. When the positive voltage was applied, only very small positive charges could drift to the grounded electrode,
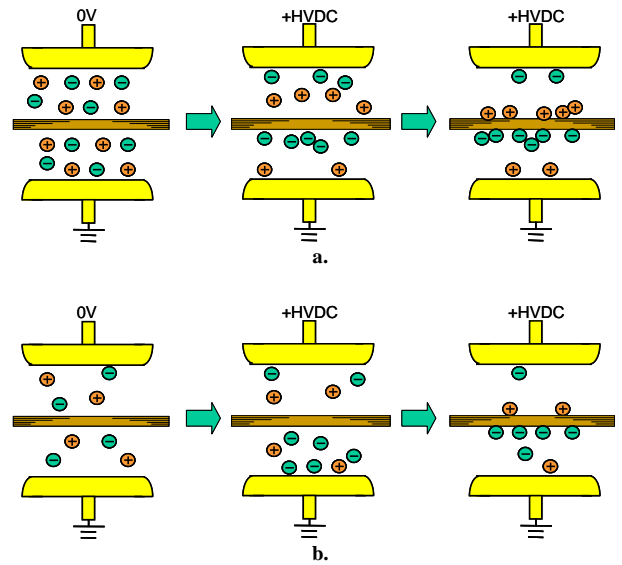
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