# Ph. D. Thesis

# RESEARCH ON CREEPING DISCHARGE PHENOMENA IN INSULATING OILS: VEGETABLE-BASED OILS AS SUBSTITUTE OF MINERAL OIL

by

# Fri Murdiya

Kanazawa Institute of Technology (KIT) Department of Electrical and Electronic Engineering, JAPAN

Supervisor: **Prof. Ryoichi Hanaoka**, Dr. Eng.

KIT vice president for research Director of Center for Electric, Optic and Energy (EOE) Applications

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# ABSTRACT

The creeping discharge phenomena developing on the insulating oil / solid insulator interface were investigated experimentally under the applied high voltages (impulse voltage and 60 Hz AC voltage). The vegetable-based oils (natural rapeseed oil and palm fatty acid ester (PFAE) oil) and commercial mineral oil (JIS C2320) were used as test sample oils in this research. Recently, the vegetable-based oils have been expected as a prospective candidate for oil-filled power apparatuses such as transformer and reactor, and they are noticed as a substitute for mineral oil, because of the demand for environmentally friendly insulating oils. The gas components dissolved in sample oils by the various discharges were also examined by the dissolved gas-in-oil analysis (DGA) technique, and the failure modes after the discharge treatment were diagnosed on the bases of the Electric Technology Research Association (ETRA) criterion and the International Electro-technical Commission (IEC) criterion using the Duval Triangle.

The behavior of creeping discharges has been investigated using two experimental models; (1) impulse creeping streamer developing in the narrow gap between two solid dielectrics and (2) AC creeping streamer developing on the oil / pressboard interface. The discharge shape, streamer extension, streamer velocity, discharge current, discharge energy, pressboard surface tracking and pressboard puncture in the vegetable-based oils are measured in detail and have been discussed in comparison with those in mineral oil. The gas components obtained from the DGA technique also enable us material evidence on the tracking mechanism on the pressboard surface. Furthermore, the behavior of creeping discharges in rapeseed oil and mineral oil with a heat-accelerated aging has been investigated in comparison with that in new oils without the aging.

From this research, it may safely be said that the electric insulation performance in the vegetable-based oils has roughly the same level as that in mineral oil. Therefore, it is concluded that the use of vegetable-based oils to the power apparatus will bring great profits from a viewpoint of the protection of the environment in the near future.

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# CHAPTER I INTRODUCTION

A petroleum-based mineral oil (the so-called transformer oil) has been most often employed in the electrical insulation inside power transformers for more than a century. Mineral oil has an excellent performance as electrical insulation and cooling medium, whereas some problems such as scarcity and high price of mineral resources in near future, sulfide-induced corrosion of copper lead to be conductive in liquid insulation, environmental pollution due to oil leakage, atmospheric pollution due to burning, etc. have been pointed out for practical use. Recently, the environmentally inoffensive vegetable-based oils are considered as substitutions of mineral oil.

A power transformer is an essential apparatus which presides over the electric power conversion and power flow. For the design of oil-filled power transformers, an electrical insulation which is composed conventionally of compound insulation systems of the insulating oil and oil-impregnated cellulose products (pressboard, kraft paper, wood etc.) is one of the most important techniques. In this case, there are several requirements for practical use of the insulation systems as follows [1-6, 71-73, 122]:

- 1. The copper windings or conductors with different electrical potential and electric field stress should be insulated effectively by the combination of insulating oil and solid insulator.
- 2. The insulating oil must play an important role as a coolant to release the heat from the core and winding to the outside of the transformer through the sink. At high temperature limit, the oil viscosity should steadily decrease to keep an oil circulating process inside the power transformer.
- The oil temperature should be controlled under its flash point in service. The chemical structure of oil should not be easily decomposed to minimize the evaporation losses.

On the other hand, J. Marc has predicted a peak of oil production for average lag of 50 years between discoveries and production in the period between 1970 and 2020. Figure 1.1 shows that the peak production will reach around 2020. Furthermore, the world production of "oil" ((1) conventional, (2) deep offshore, and (3) extra-heavy) has

almost stopped growing in 2005. The vertical black line refer to 2010 show the oil production in the true sense refers to the sum of (1) conventional, (2) deep offshore, and sometimes (3) extra-heavy slightly decreased while NGL (natural gas liquid), refinery gains, CTL (coal to liquid), biofuel etc. will rise until to peak point in 2020 [124].

L. D. Roper has also reported about the prediction of crude oil price. Figure 1.2 shows that the crude oil price increases exponentially until 2020 [125].



**Figure 1.1** Simulation of world production of liquids, in billion barrels per year, for ultimate reserves of approximately 3500 billion barrels.



**Figure 1.2** Prediction of crude oil price until 2020.

Actually, the mineral oil contains several atoms such as hydrogen, carbon, a few sulfur atoms, etc. When the power transformer energizes under high voltage, high temperature or chemical and physical processes, sulfur atoms lead to copper sulfide which is more conductive than insulating oil. Such the decay product attributes to fault in the transformer. There are some investigations on the effect of copper sulfide in high voltage engineering.

F. Scatiggio *et.al.* has investigated on the nature and causes of corrosive sulfur induced failures in the oil-filled transformer and shunt reactor. Copper sulfide occurs when sulfur in mineral oil reacts actively to copper conductors, and this can diffuse into the paper insulator covering the winding. Then, it leads to the increase of the dielectric loss [7]. P. Wiklund *et.al.* has investigated on the copper dissolution and metal passivator in insulating oil to overcome the oil insulation problem, and they have reported that a passivator acts so as to prevent the copper dissolution in power transformer [8]. Furthermore, the duration and mechanism for suppressive effect of triazole-based passivators such as 1, 2, 3-benzotriazole (BTA) and Irgamet 39/sup TM/(CIBA Specialty, Basel, Switzerland) on copper-sulfide deposition on insulating paper in transformers and reactors have been reported by T. Amimoto *et.al.* [9-10]. They have examined the heating process on the suppressive effect of copper-sulfide deposition by using bare and paper-wrapped copper plates in mineral oil that refers to the specification of IEC 60296.

Recently, the global trend suggests to finding friendly environmental materials. The development of an environment-friendly insulating liquid has been paid attention for a new design of oil-filled power apparatus such as transformer, capacitor, and load tap changer. The vegetable oils have a biodegradable property higher than the mineral oil and silicone oil, and the discharge of  $CO_2$  in burning is nothing. This can adapt to the environmental protection with the offering of a carbon neutral [1, 11-12, 69-71, 74-78]. The vegetable oils also are renewable materials and many countries in the world can produce these oils.

Nowadays, the countries such as USA, Europe and Japan have focused on the vegetable oils (origin from rapeseed, soybean, sunflower, palm fruit, etc.) as a sustainable and friendly–environmental material. Because vegetable-based oils such as palm fatty acid ester (PFAE) oil and rapeseed oil have many advantages on the

environmental compatibility and electrical insulation performance, they are expected for insulation design of an environmentally fitted power transformer.

The comparison between mineral oil and vegetable-based oils on the partial discharge, creeping discharge and electrical breakdown phenomena has been investigated by many researchers for the last ten years. Oil-solid interfaces of the compound insulation system in oil-filled power transformers will be concerned as electrical weak point which the creeping discharges are easier progress, because of the difference in permittivity between adjacent materials. The irreversible tree-like damage (tracking) occurs on the solid surface as a result of these creeping discharges, and it results in a permanent electrically conductive path that deteriorates a function of insulation system. To guarantee a level of electrical insulation under high electrical stresses, the understanding of creeping discharge phenomena is most important for a designer who expert in the oil insulated power apparatuses.

## **1.1 BACKGROUND OF RESEARCH**

In the present research, there are several problems to be solved from an insight for practical use of vegetable-based oils as an electrical insulation material:

- We must be clear what the kinds of dissolved gas and fault in oil samples (mainly, rapeseed oil and mineral oil) caused by various discharges; impulse or ac creeping discharge, partial discharge (PD) and arc discharge. A dissolved gas-in-oil analysis (DGA) can be examined by means of a gas chromatograph (GC) with a stripping method refer to Duval triangle and Electric Technology Research Association (ETRA) standard diagnostic of power transformer (ETRA type A and B). In the DGA, generally, seven gas components; hydrogen (H<sub>2</sub>), methane (CH<sub>4</sub>), ethane (C<sub>2</sub>H<sub>6</sub>), ethylene (C<sub>2</sub>H<sub>4</sub>), acetylene (C<sub>2</sub>H<sub>2</sub>), carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) are chosen as a target of gas analysis.
- 2. The flashover in the insulation system inside oil-filled power apparatuses, generally, pursues a complicated course of streamer progression including the oil/pressboard interface, narrow gap between pressboards, pressboard punch-through breakdown and so on. We must be clear that how the creeping streamers progressed in the dielectric barrier with narrow gap (available small oil volume) inside the oil samples behave under the impulse voltages (simulating lightning surges). The

measurements of the discharge shape and associated current, streamer length and flashover voltage, temporal variation of steamer growth under variable impulse voltage of the positive and negative polarities with 1.2/50 µs and 1.2/1000 µs waveforms are required in this experiment.

- 3. The transformers, usually, are worked under AC high voltage with 50 or 60 Hz. We must be clear that how the creeping streamers developing on the oil/pressboard interface inside the vegetable-based oil samples (rapeseed oil and PFAE oil) and mineral oil behave under the AC voltages. The measurements of the discharge shape and associated current, streamer extension, streamer velocity, pressboard surface tracking, pressboard puncture, discharge energy and emitted light, as a function of both the time and voltage under variable AC 60 Hz voltages up to 40 kV in effective values are required in this research.
- 4. We must be clear that how the creeping streamers developing on the oil/pressboard interface inside aged oil samples (mainly, rapeseed and mineral oils) behave under the AC voltages (or impulse voltages). The experimental data in aged oil samples are necessary to consider in comparison with the data in new (non-aged) oil samples.

## **1.2 RESEARCH OBJECTIVES**

This research is focused to the following items as an objective:

- To analyze the dissolved gases in both rapeseed oil and mineral oil caused by various discharges and to identify the kind of fault using Duval Triangle and ETRA type A and B.
- 2. To make clear the behaviors of creeping streamer progressed in the dielectric barrier with narrow gap in PFAE oil and mineral oil under variable impulse high voltage of the positive and negative polarities with  $1.2/50 \ \mu s$  and  $1.2/1000 \ \mu s$  waveforms.
- 3. To make clear the behaviors of creeping streamers developing on oil/pressboard interface inside the vegetable-based oil samples (rapeseed and PFAE oils) and mineral oil under the AC high voltage.
- 4. To make clear the behaviors of AC creeping discharge developing on oil/pressboard interface inside aged oil samples (rapeseed and mineral oils), in comparison with

the behaviors in new oil samples.

All experiments are performed at room temperature in the atmospheric pressure.

### **1.3 GUIDELINES OF PAPER**

This paper is composed of seven Chapters as follows:

- Chapter I is "Introduction" of this paper, which is including the background of research, research objectives and guidelines of paper.
- Chapter II reviews about the past investigations on the physicochemical and electrical properties of vegetable oils, electrical conduction characteristics in insulating liquids under uniform and non-uniform electric fields, space charge effect and its polarity effect in non-uniform electric field, creeping discharge phenomena in insulating oils and dissolved gas-in-oil analysis (DGA) in insulating oil (mainly mineral oil).
- Chapter III explains about the component of gases dissolved in natural rapeseed oil and mineral oil by several discharges (impulse arc discharge, AC creeping discharge, etc.). In this Chapter, the experimental set up and method of a dissolved gas-in-oil analysis (DGA) are indicated and the diagnostic evaluation of rapeseed oil based on the DGA has been presented in comparison with that of mineral oil.
- Chapter IV explains about the properties of creeping discharge progressed in the narrow gap between two solid dielectrics in PFAE oil and mineral oil under the applied lightning impulse voltage. The experimental setup and procedure in this research are presented in detail. The distinctive results on the progression of creeping streamer and flashover voltage have been obtained from the experiment and they have been discussed in this chapter.
- Chapter V explains about the behavior of AC creeping discharges in vegetable-based insulating oils (rapeseed oil and PFAE oil) and mineral oil. In this research, the discharge shape, streamer extension, streamer velocity and tracking on pressboard surface have been examined as a function of the time and voltage under variable AC 60 Hz voltages up to 45 kV<sub>rms</sub> (root- mean-square values). The experimental preparation, setup and procedure are presented in detail. The several phenomena accompanying AC creeping discharges have been

discussed on the basis of the experimental results.

- Chapter VI explains about the behaviors of creeping discharge in rapeseed oil and mineral oil with a heat-accelerated aging to obtain further understanding of creeping discharges on the oil/pressboard interface. In this Chapter, the aging effect of oils on the discharge shape, streamer extension, streamer velocity, discharge current waveforms, discharge energy, pressboard surface tracking and pressboard puncture under the applied AC high voltages are presented in comparison with the creeping discharge events in new oils without the aging.
- Chapter VII is "Conclusions", which is summarizing an important outcome obtained by an accomplishment of the present research. The suggestion for future research and a problem to be solved have also been stated.

## **CHAPTER II**

# BACKGROUND ON THIS RESEARCH (Literatures Review)

# 2.1 PHYSICOCHEMICAL AND ELECTRICAL PROPERTIES OF VEGETABLE -BASED OILS

Esters are utilized today for the liquid insulation in high voltage apparatuses such as transformer. The esters usually have higher dielectric losses than mineral oil because of higher dielectric constant. However, in the solid/liquid insulation systems, the esters can avoid the concentration of high electric field, because it can reduce the difference in dielectric constant between adjacent materials (solid and liquid). Though these esters have also higher conductivity, larger ability to dissolve water and higher viscosity, the main advantages of esters are that have a high flash point (more than 300 °C in natural esters, compared to ~ 150 °C in mineral oil), higher biodegradability and non-toxic [78].

Generally, there are two main types of esters as follows [56]:

## (a) Natural esters

Natural seed-oil esters were studied to oil-filled power transformers for past decade, even though rapeseed oil considerably implemented in capacitor and held a dominant potential. However, natural seed is susceptible to oxidation that is a poser as liquid insulation material. The chemical structure of natural ester oil is presented in Figure 2.1.

## (b) Synthetic esters

Synthetic ester dielectric has suitable dielectric properties and is more sharply biodegradable than mineral oil. To produce this liquid dielectric, it needs higher cost than other less-flammable liquid dielectrics. Since 1984, synthetic ester dielectrics were used as an alternate of askeral oil contained PCBs (poly chlorinated biphenyls). Figure 2.2 shows the chemical structure of synthetic ester oil.



Figure 2.1 Chemical structure of natural ester oil.



Figure 2.2 Chemical structure of synthetic ester oil.

The synthetic ester oil has some advantages in physical properties as follows:

- 1. Low vapor pressure,
- 2. Low volatilities
- 3. High flash point.
- 4. High lubricity.
- 5. High solvency.
- 6. Higroscopic.
- 7. High thermal stability
- 8. High hydrolytic stability.

The comparison of general characteristics between mineral oil and ester oil is shown in Table 2.1 [126].

**Table 2.1** Characteristic comparison between mineral oil and ester oil.

Criteria	Mineral oil	Ester oil		
Key properties	Non-renewable material	Renewable sources		
Environmental	Poorly biodegradable and	Highly biodegradable and		
properties	slightly toxic	non-toxic		
Leaks and spill	Spills clean-up are required by	Spills clean up can be		
	regulation.	eliminated because relatively		
	rapid biodegradable.			

Many researchers are now searching new types of liquid insulating materials, which are generally organic types and obtained from the nature. The new liquid insulating materials must be biodegradable and friendly to the environment. Many natural esters consist of additive chemical packages such as oxidation inhibitors, metal deactivators, depressants to minimize the pour point and aid for the oxygen stability. In some cases, they have an antimicrobial agent or copper deactivators, while in mineral oil there is either no additives or merely oxidation inhibitors. It cannot be predicted what any adverse characteristics still exist if natural esters are filled into transformers over a long period [79, 127].

A vegetable oil was considered as the most likely candidate for a fully biodegradable insulating fluid. This is a natural resource available in plenty; it is a fairly good insulator and is fully biodegradable. The researchers soon recognized that vegetable oils needed further improvement to be used as a transformer fluid. The fluid in a sealed transformer remains with the unit for many years (as many as 30 to 40 years, unless the oil is changed in between times). Vegetable oils inherently have components that degrade in a relatively short time. The degree of unsaturation is an indicator of thermal instability, becoming no more stable as the degree of unsaturation progresses from mono- to tri-unsaturation. The relative instability to oxidation is roughly 1:10:100:200 for saturated, mono-, di- and tri-unsaturated C-18 triglycerides [79].

In transformers, the presence of copper (as a conductor) enhances tendency for oxidation. Powerful oxidation inhibitors are needed for the oils used in transformers. Another factor is the purity of the oil. The oil has to be free of conducting ionic impurities to acceptable levels, and commercial-grade oils are not of this purity. The compositions of fatty acid in several vegetable oil are described in Table 2.2 [128].

There are some challenges of vegetable oil for the use of power transformers:

## 1. Cold weather

If the power transformers filled with vegetable-based oils are exposed to cold weather below -30 °C, the pour point of vegetable-based oils does not have satisfactory performance, even though after adding a rising depressant of the pour point.

#### 2. Exposure to air

To avoid an invasion of air and moisture from the outside, the vegetable based oil-filled power transformer should seal a container hermetically during operation. The

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vegetable based oils can be oxidized with air and moisture from the outside and then produce decay product. This leads to the deterioration of the oils.

Due to environmental consideration, recently many researchers have carried out an attempt to search the substitutes of mineral insulating liquids, which are friendly to the environment. Palm kernel *(Eheis guineensis)* is one of the most famous raw materials for vegetable oil. Palm grows well in Africa, Asia and north and South-America.

Indonesia produces ~ 44 % of world's palm oil and Malaysia produces ~ 41 %, and other countries including Nigeria, Thailand, Colombia, Ecuador, Papua New Guinea, Ivory Coast and Brazil etc. produce ~ 15 % [129]. Crude palm oil (CPO) can be obtained from a mesocarpic layer of palm fruit. Palm oil contains 96.2 % of neutral fat (lipid) and 3.8 % polar fat. The majority of the polar fat is an unsaturated phospholipid [58]. The investigation of the CPO as an alternative liquid insulator was carried out in recent years. The dielectric properties, breakdown voltage and losses factor of crude palm oil (CPO) are influenced by the polar fat content in the CPO.

Vegetable oil	Saturated fatty acid, %	Unsaturated fatty acid, %		
	-	Mono-	Di-	Tri-
Canola oil*	7.9	55.9	22.1	11.1
Corn oil	12.7	24.2	58	0.7
Cottonseed oil	25.8	17.8	51.8	0.2
Peanut oil	13.6	17.8	51.8	0.2
Olive oil	13.2	73.3	7.9	0.6
Safflower oil	8.5	12.1	74.1	0.4
Safflower oil, high oleic	6.1	75.3	14.2	-
Soybean oil	14.2	22.5	51	6.8
Sunflower oil	10.5	19.6	65.7	-
Sunflower oil, high oleic	9.2	80.8	8.4	0.2

**Table 2.2**Composition of fatty acid.

\* Low erucic acid variety of rapeseed oil; more recently, canola oil containing over 75% monounsaturate content has been developed.

The method to reduce polar fat is by bleaching and deodorizing process or refined bleaching and deodorized palm oil (RBDPO). The quality of oil depends on the stearin or fat content. The other samples such as CPKO (crude palm kernel oil), CCO (crude coconut oil) and RCO (refined coconut oil) have also been examined. The investigation is concerned in the dielectric dissipation factors and breakdown voltages of the oils as function of temperature. The investigation on the properties of these vegetable oils has been carried out in comparison with that of mineral and silicone oils. According to the existing standard such as the International Electro-technical Commission (IEC), American Society for Testing and Materials (ASTM) or British standard, some of the oils such as RCO and RBDPO may be used as alternatives for liquid insulating materials [80, 85].

Palm fatty acid esters (PFAE) such as methyl octanoate, methyl dodecanoate, 2-ethylhexyl octanoate and 2-ethylhexyl dodecanoate are not only higher dielectric breakdown but also have fluidity higher than mineral oil. However, PFAE oils have moisture content higher than mineral oil. It is seem that high moisture content in PFAE oils can against breakdown voltage as compared with mineral oil. Figure 2.3 shows the relationship between breakdown voltage and moisture content for several oils. The



**Figure 2.3** Breakdown voltage at 2.5-mm gap versus moisture content in mineral oil (filled diamonds) and in various fatty acid esters at room temperature (~25 °C): C8-Me (filled squares), C12-Me (filled circles), C8-2EH (open squares) and C12-2EH (open circles). The fatty acid esters have higher resistance to electrical breakdown than mineral oil. [13]

breakdown voltage in mineral oil decreased sharply by slight moisture content, while in PFAE oils, it decreased gradually versus moisture content. Table 2.3 shows number of ester molecules per one H<sub>2</sub>O molecule [13].

The dielectric properties of vegetable oils have been found in several standards such as the International Electro-technical Commission (IEC) and American Society for Testing and Materials (ASTM) standards. Table 2.4 shows the properties of vegetable oils (PFAE oil and rapeseed oil) compared with mineral oil.

	_	_	
	Moisture contents	Number of ester molecules per	
	(ppm)	one H <sub>2</sub> O molecule	
C8-Me	3,946	28.8	
C10-Me	2,801	34.5	
C12-Me	2,094	40.3	
C14-Me	1,638	45.4	
C8-2EH	1,273	55.2	
C10-2EH	1,133	55.8	
C12-2EH	930	61.9	
C16-2EH	781	62.7	

**Table 2.3** Saturated moisture contents in methyl ester and in 2-ethyl esterhomologs at room temperature (~ 25 °C). [13]

**Table 2.4**Main properties of insulating oil. [6]

Physical and electrical J	properties	PFAE oil	Rapeseed oil	Mineral oil
Density (20°C)	g/cm <sup>3</sup>	0.86	0.92	0.88
Kinetic viscosity (40°C)	mm²/s	5.06	36.0	8.13
Pour point	°C	-32.5	-27.5	-45.0
Flash point	°C	176	334	152
Toxicity		non- toxic	non- toxic	slightly toxic
Ability to biodegradability		high	high	low
Breakdown voltage (Moisture level: 10 ppm or less)	kV/2.5mm	81	74	70-75
Relative permittivity (80°C)		2.95	2.86	2.2
Dissipation factor: $\tan \delta$ (80	)°C)	$3.1 \times 10^{-3}$	$8.3 \times 10^{-2}$	$1.0 \times 10^{-3}$
Volume resistivity (80°C)	$\Omega \cdot cm$	$7.1 \times 10^{12}$	$4.4 \times 10^{12}$	$7.6 \times 10^{15}$

PFAE oil and rapeseed oil are better than mineral oil for the environment safety, because of an excellent biodegradability and a non-toxic. A flash point of PFAE oil and rapeseed oil are higher than mineral oil, and they cannot only generate dioxins but also toxic products in the fire. A kinetic viscosity is lower in PFAE oil. However, it is very higher in natural rapeseed oil as compared with mineral oil. PFAE oil and rapeseed oil are also profitable for the coordination in permittivity between adjacent materials, because of their high relative permittivity. The electric breakdown voltage is better than mineral oil at low moisture level conditions, which is advantageous for an electrical insulation in the oil/pressboard compound insulating system. PFAE oil and rapeseed oil, however, have a high moisture saturation limit (~ 2500 ppm at 20 °C), since it is prone to take up water in chemically bonded form or in dissolved form. This will affect in the increase of the dissipation factor (tan  $\delta$ ) and reduction in the volume resistivity as compared with mineral oil. [6]

Previous investigation on the vegetable-based oils such as rapeseed oil as the substitute of transformer oil has already been compared to mineral oil (Shell Diala D) and the result has been shown that the electrical insulation properties of rape-seed oil are similar to them of mineral oil. Particularly, 50 Hz ac breakdown voltage is similar to mineral oil, and the specific DC resistance and dielectric dissipation factor reach the IEC standard. In this investigation, the chemical, physical and electrical properties have also been estimated and analyzed as follows [81-84].

In order to estimate lifetime or dielectric problem of the vegetable based oils, the quality of these liquid insulations is an important view. Overheating of windings leads to the degradation in the molecular structures of oil/pressboard. There are some challenges have to pay attention.

- 1. The vegetable based oils have a moisture level much higher than mineral oil. They can interact with cellulose.
- 2. Physical properties such as the temperature distribution should be considered.
- 3. Polymerization degree of the vegetable based oil makes better behavior for the aging than mineral oil.
- 4. In breakdown test under the AC voltage, it was reported that the vegetable based oils are below mineral oil.
- 5. The dielectric strength of the vegetable based oils is not consistent between the

lightning and switching impulse voltages in oil/pressboard system.

6. Innovative setups such as test arrangement for an oil/board insulation system and advance analysis are needed [87-88].

# 2.2 ELECTRIC CONDUCTION PROPERTIES IN LIQUID DIELECTRICS (Relationship between Current and Applied Voltage)

## 2.2.1 Uniform Electric Field Case

When a DC voltage is applied to the parallel plate electrodes in the pure liquid dielectrics, the relationship between current and voltage (the so-called electric conduction characteristic) is obtained as shown in Figure 2.4.

In characteristics of Figure 2.4, region A indicates that the voltage and current is proportional, region B indicates the steady-state current value and region C indicates that the current increases rapidly with increasing of the voltage. Electric conduction in each region is different from the characteristic in the gases, and it is described as follows:

- 1. **Region A:** This area is considered as an insulator (liquid dielectric) with a constant resistivity, and the current increases linearly with the voltage due to ionic conduction. In this area, both positive and negative ions are generated by an ionization in liquid molecules due to the effect of ultraviolet (UV) light.
- 2. Region B: In this region, there is constant ion production rate in the liquid, even



**Figure 2.4** Relationship between current I and voltage V under uniform electric field in liquid dielectrics [59].

when the voltage rises. Then, the current in this region indicates the tendency of saturation. The relation like this, however, does not explicitly appear in ordinary liquid dielectrics, although it is recognized in hexane etc. with high purity. One has referred to the electric conduction in the regions A and B as "low-electric field conduction".

3. **Region C:** When the voltage is further increased, the current sharply increases and it tends to the spark discharge in the end. One has referred to the electric conduction in the region C as "high- electric field conduction". This conduction region is closely related to the spark discharge phenomenon [59-60].

## 2.2.2 Non-uniform Electric Field Case

The electrode configurations such as the needle to plate electrode or razor blade to plane electrode form an extremely unequal electric field in the gap, so that the electric conduction characteristic in the liquid dielectrics is largely different from that in the parallel plate electrodes. The electric field strength at the tip of the needle or blade electrode significantly increases, even if the applied voltage is relatively low. Therefore, charged particles are injected into the liquid from the surface of electrode tip and the current rises sharply by the slight increase of the voltage. In general, the relationship between current and voltage (electric conduction characteristic) is obtained as shown in Figure 2.5.



**Figure 2.5** Relationship between current I and voltage V under non-uniform electric field in liquid dielectrics [59].

In this figure, since the current values change very largely by the increase of the voltage, the current value I on the vertical axis is taken as "ln (I)". Figure 2.5 consists of the four areas; "region A" which the voltage and current is proportional, "region B" which the current rapidly increases, "region C" which shows a tendency of saturation current and "region D" which is the breakdown area, as mentioned below.

- 1. **Region A:** This region is thought to be due to ionic conduction, which is similar to the region A of the characteristics (Figure 2.4) in the uniform electric field, and Ohm's law is kept. In the needle to plate electrode in transformer oil, the current value is of the order of approximately  $10^{-12} \sim 10^{-10}$  A (This is the area in dark current).
- 2. Region B: The current increases rapidly when the voltage reaches the critical value. This region shows that the charged particles are injected into the liquid from the tip of sharp electrode (needle or blade electrode). On the injection mechanism of charged particles, when the negative voltage is applied to the sharp electrode, it will be due to the electron emission based on the Schottky's theory for the liquid dielectrics at the room temperature. In this case, the emitted electrons, usually, are trapped into the liquid molecules or impurities, and they result in the negative ions. If the positive voltage is applied the sharp electrode, the positive ions will occur near the electrode tip by the mechanism based on the field ionization, that is the high electric field at the sharp electrode tip can produce the positive ions by the electron avalanches.
- 3. **Region C:** When further the voltage increases, the increase of the current is restrained and the current curve shows a tendency to saturate. This is due to the space charge effect on the electric field at the electrode tip. That is, since the charged particles near the electrode tip which act as a space charge are homo-charge, the electric field at the tip is reduced by this space charge and the injection of charged particles is suppressed. The current in this region is said the space charge limited current (SCLC). This is a characteristic of the electric conduction in liquid dielectrics.
- 4. **Region D:** When the applied voltage reaches the threshold value in the electrical breakdown of the liquid dielectrics, a spark discharge occurs and the current increases rapidly. On the electrical breakdown phenomena in liquid dielectrics, the

breakdown theory caused by the bubble formation process, electronic process, corona discharge, impurities etc. have been investigated [59-60].

#### 2.3 THEORETICAL ANALYSIS ON NON-UNIFORM ELECTRIC FIELD

The oil/pressboard compound insulating system has most often been adopted in the electrical insulation design inside an oil-filled power apparatus such as power transformer. Generally, the electrical accidents such as flashover and puncture events in the oil/pressboard interface are significantly influenced in the non-uniform electric field rather than the uniform electric field at same level of the voltage. A needle to plane electrode geometry is one of most fundamental electrode arrangements to analyze various discharge phenomena in the non-uniform electric field. The electric field distributions in the gap of needle to plane electrode geometry has been investigated mathematically by several researchers using the electrode model as shown basically in Figure 2.6, and they are formulated as mentioned below [14].

#### 1. Duran and Mason Model

In this model, an ellipsoid system of coordinates  $((\mu, v, \varphi)$  is used to formulate the electric field in a point P( $\mu$ , v) of the domain with axial symmetry D (see Figure 2.6), and the formula on the electric field is represented as follows;



Figure 2.6 Typical model of needle - plane electrode geometry.
D: domain of calculation, S<sub>1</sub>: hyperbolical surface,
S<sub>2</sub>: plane surface, S<sub>3</sub>: ellipsoidal surface, x: x-axis and y: y-axis (axial symmetry).

where *U* is the potential to electrodes  $(U = V_1 - V_2)$ , *d* the gap between the electrodes,  $c = \sqrt{d^2 + dr_0}$  the focal distance of the homo focal hyperboloids and ellipsoids,  $A = \ln \frac{(c+d)}{(c-d)}$  a constant and the coordinates are  $\mu \in [1, \infty]$ ,  $v \in [0, \frac{d}{c}]$ ,  $\varphi \in [0, 2\pi]$ .

## 2. Nothinger Model

The formula in this model is represented as follows;

$$E_{N(y)} = E_{\max,N} \frac{dr_0}{dr_0 + 2dy - y^2} \qquad (2)$$

where the position of  $y = d - c\mu v$ , i.e the electrode tip is the coordinate origin (see Figure 2.6)

#### 3. Coelho and Debeau Model

The formula in this model is represented as follows;

$$E_{C(y)} = E_{\max,C} \frac{dr_0 + \frac{r_0^2}{2}}{dr_0 + \frac{r_0^2}{2} + 2dy - y^2} \dots (3)$$

## 4. Bamji Model

The formula in this model is represented as follows;

$$E_{B(y)} = E_{\max,B} \frac{dr_0}{dr_0 + 2dy - y^2} \quad \dots \qquad (4)$$

The above formulas;  $E_{N(y)}$ ,  $E_{C(y)}$  and  $E_{B(y)}$ , denote the values of the electric field intensity in the point P(y) placed at the distance y from the needle tip, where the maximum electric fields is represented as follows, respectively.

$$E_{\max,N} = \frac{2U\sqrt{1+\frac{r_0}{d}}}{r_0 \ln\left[\frac{\left(2d+r_0+2d\sqrt{1+\frac{r_0}{d}}\right)}{r_0}\right]} \dots (5)$$

$$E_{\max,C} = \frac{2U}{r_0 \ln\left(2+\frac{4d}{r_0}\right)} \dots (6)$$

$$E_{\max,B} = \frac{2U}{r_0 \ln\left(1+\frac{4d}{r_0}\right)} \dots (7)$$

Mason also obtained the following expression on the maximum electric field;

$$E_{\max,M} = \frac{2U\sqrt{1+\frac{r_0}{d}}}{r_0} \frac{1}{\ln\left[\frac{\left(2d+r_0+2\sqrt{d^2+dr_0}\right)}{r_0}\right]}$$
(8)

and Ashcraft obtained the following expression;

$$E_{\max,A} = \frac{2U\sqrt{1+\frac{r_0}{d}}}{r_0} \frac{1}{\tanh^{-1}\left(\frac{1}{\sqrt{1+\frac{r_0}{d}}}\right)} \quad .....(9)$$

The equation (9) can be simplified to calculate both maximum and minimum electric fields used in the investigation as follows [61]:

$$E_{y} \approx \frac{U}{\ln\left(\frac{4d}{r_{0}}\right)} \frac{d}{d(2y+r_{0})-y^{2}} \qquad (10)$$

$$E_{\min} \approx \frac{2U}{\ln\left(\frac{4d}{r_{0}}\right)} \frac{1}{d} \qquad (11)$$

$$E_{\max} \approx \frac{2U}{\ln\left(\frac{4d}{r_0}\right)} \frac{1}{r_0} \quad \dots \tag{12}$$

# 2.4 SPACE CHARGE EFFECT AND ITS POLARITY EFFECT IN NON-UNIFORM ELECTRIC FIELD

The scalar potential and electric field distribution in the solid insulating materials or oil/pressboard insulation systems are, usually, analyzed mathematically under uncharged condition, both in volume and on the surface. However, this is not true in the practice under the discharge conditions, because the partial discharge or creeping discharge is accompanied with the electric conduction in volume or on the surface of the materials and it leads to volume charges. Therefore, the potential and electric field distributions cannot be computed by Laplace's equation from knowledge of the electrode geometries and properties of dielectric materials, because the system is then derived by Poisson's equation. Thus, the conduction laws should be known to calculate the surface and volume charge distributions. If the charge injection and its transportation are related to the electric field which depends on the charge distribution through Gauss's law, the electric field and charge distributions must be self-consistenly determined. It is well known that the negative charges (electrons) are injected from the negative needle and they can be accumulated on the pressboard/oil interface.
The space charge effects on the electric field distribution in mineral oil have been investigated by M. Zhan and R. Hanaoka using the Kerr electro-optic field mapping measurements and Abel transformation, for the thin or thick needle to plane electrode geometries with and without transformer pressboard on the plane electrodes [90]. The distortion in the electric field distributions due to the volume space charge in the oil and surface charge accumulated at the oil/pressboard interface can be examined by measuring the rms distributions of  $I_{\omega}/I_0$  taken for light directed perpendicular to the electric field using the Kerr electro-optic technique, where  $I_0$  is the detected light intensity when no voltage is applied and  $I_{\omega}$  the detected light intensity with a component at the fundamental AC frequency  $\omega$ .



**Figure 2.7** Typical rms distributions of  $I_{\omega}/I_0$  along pressboard surface (y-direction) [90].

In this investigation, the space charge effects for the thin needle - plane electrode geometry with pressboard on the plane electrode were not significant for a positive needle, because the theoretical space charge free curves and experimental curves (the solid symbols) have similar distribution as shown typically in Figure 2.7. Large charging effects were found with a negative thin needle, because the electric field along electrode is the thin needle –plane geometry, gap spacing  $d_0$  is 3.5 mm and pressboard thickness is 1 mm. Solid symbols are data for positive needle and hollow symbols for negative needle [90]. The pressboard surface (the hollow symbols) is very lower than the theoretical space charge free curves. These results in the negative needle, however, become opposite for the electrode geometry without pressboard on the plane electrode, which means that has a larger electric field than the space charge free case. This indicates that the negative charges injected from a negative needle are significantly accumulated as a negative surface charge on the oil/pressboard interface shielding the oil region with a similar electric field and the pressboard has a larger electric field.

On the other hand, the space charge effect and polarity effect on the electric field distribution have been considered in relation to the breakdown voltage  $V_b$  in the electrode geometries which form a non-uniform electric field in gases [62]. Figure 2.8 (a) displays the process of the space charge effect in a positive needle-plane gap. Firstly, an ionization phenomenon is taken place by the electron collision at the high electric field region close to the needle tip. The electrons with higher mobility due to the high electric field can be readily drawn into the anode (positive needle electrode), then the positive space charge is left at the region near the needle tip. This positive space charge will lead to a reduction in the field strength close to anode and it will increase the field in the gap further away from there. The field strength at the tip of the space charge may be high enough for the initiation of a cathode-directed streamer. This means that is easy to induce the complete breakdown.

The field distortion in a negative needle-plane gap is illustrated along with the positive space charge as shown in Figure 2.9. The electrons emitted from the negative needle tip progress toward the anode (positive plane electrode), then it will be accompanied with the collision ionization due to the energy of electrons obtained from the electric field. Consequently, the positive space charge remains in the space (ionization region) between the negative charge and the negative needle. By this

positive space charge, the electric field at the needle tip is grossly enhanced, but the field in the ionization region is drastically reduced, so that, a higher voltage is required for the initiation of a cathode-directed streamer.

As a result, the negative breakdown voltage is higher than the positive breakdown voltage in the needle-plane electrode geometry, namely,  $V_b$  (positive needle)  $< V_b$  (negative needle).



Figure 2.8 (a) Space charge build-up in positive needle to plane gap.(b) Field distortion formed by space charge [62]



Figure 2.9 (a) Space charge build-up in negative needle to plane gap.(b) Field distortion formed by space charge [62]

# 2.5 PAST INVESTIGATIONS ON CREEPING DISCHARGE AND SPACE CHARGE IN INSULATING OILS

Creeping discharges in insulating oils are the expanded phenomena of a partial discharge. These are accompanied by the progression of streamers, emitting of light spots, many branches and extension in the length and width, and the medium will be more conductive by the occurrence of these discharge. The creeping streamer which occurs along the solid surface from a high voltage electrode in a solid/liquid insulation system can lead to the flashover through a grounded electrode by its progression. Figure 2.10 shows the typical aspect of streamer in the oil/pressboard insulation system.

The white marks which resemble the creeping discharge shape, generally, appear in the pressboard surface along with the development of a conducting path at the oil/pressboard interface. This is attributed to creeping discharge with high enough energy to dry out the pressboard, and the creeping discharge produces gases in the pressboard surface by the decay oil molecules. During the creeping discharge, the leakage current may flow intermittently. This is sometimes visible in the form of an arcing discharge bridging between the needle tip and the grounded electrode at the oil/pressboard interface [15].

### 2.5.1 Investigations on Creeping Discharge in Mineral Oils

In the past, numerous investigations in mineral oil have been carried out under several experimental conditions, such as the gap spacing, the wave form and polarity of impulse voltages, AC and DC voltages, the temperature and pressure of the oil, the electrode arrangements, the insulation systems (in liquid and in solid/liquid compound system) etc., and they are reviewed as follows.



**Figure 2.10** Typical example of streamer in oil/pressboard insulation system in insulating oil.

The positive streamer propagation in large needle-plane gaps in mineral oil has been investigated under impulse voltage [16-17]. This investigate was focused on the influence of gap distances in the range  $\leq 35$  cm using the voltages from streamer inception up to large over voltage. The measurements are concerned with the time to breakdown, the breakdown voltage, visualization of streamers recorded by streak and still photographs, electrical properties including the transient current and charge, light emission intensity, electric field strength and the determination of the potential drop along streamers. Figure 2.11 presents the streak photograph and associated signals for the typical 2nd mode streamer below the breakdown voltage  $V_b$  in the gap distance d=20cm and applied voltage V=256 kV. For  $V < V_b$ , at the time at  $t = t_1$ , the streamer with a weak luminous light propagates, and it has numerous branch with thin filaments and ~ 10 µm in diameter. Then, the discharge current is relatively small. The discharge



**Figure 2.11** Streak photograph and associated signals for typical 2nd mode streamer below the breakdown voltage  $V_b$ . d=20 cm, V=256 kV. [16]

current becomes larger than that of the first stage. Final stage shows the stopping of streamer which does not reach to the plane electrode because of below the breakdown voltage.

The correlation between streamer velocity and propagation modes had a qualitative agreement that was already found from the calculation and observation. Streamers are characterized and then classified into different modes (2nd, 3rd and 4th modes) according to their propagation velocities up to more than 100 km/s. The existence of various streamer modes (2nd, 3rd and 4th modes) is according to the applied voltage (see figure 2.12). Figure 2.12 shows streamer velocity developing slowly with the increase of the applied voltage in the range of the breakdown voltage  $V_b$  to critical voltage  $V_a$ . The transition streamer velocity between slow modes ( $2^{nd} + 3^{rd}$ ) and fast modes ( $3^{rd} + 4^{th}$ ) occurs at the electric field which the streamer exceeds ~ 400 kV/cm. This value is the minimum field required for the development of fast streamers with rod electrodes. From this investigation, it is also found that the streamer occurs in a narrow gaseous channel. The positive streamer in mineral oil will has a lot of branches when the applied voltage is increased [17].

The phenomena on transition to fast streamers in mineral oil in the presence of insulating solids have been reported [91]. Figure 2.13 shows average streamer velocity



**Figure 2.12** Average streamer velocity versus applied voltage (d=10 cm). [17]



**Figure 2.13** Average streamer velocity versus applied voltage in the liquid with and without a solid parallel to the field (d=10 cm).[91]

versus applied voltage in the liquid with and without a solid parallel to the field (d=10 cm). It is shown that the average velocity slowly increases from 2 to 3 km/s at around the breakdown voltage  $V_b$  in the liquid with and without a solid interface. In the liquid with a solid interface, the applied voltage reaches to the critical value at 260 kV and the average velocity begins to rise strongly with the increase of applied voltage. However, in the liquid alone, the average velocity still slowly grows from 2 to 3 km/s in the range of  $V_b$  to  $2V_b$ . When the applied voltage reaches to the critical value at 360 kV, the average velocity also starts to increase strongly with increasing the applied voltage.

Another investigation on the transition to fast streamers in mineral oil has been carried out as well under the impulse voltage of negative polarity [18]. A sheet of solid insulation (Kraft board) was vertically immersed in a large tank filled with commercial mineral oil. The back side of Kraft board is equipped with a ground electrode (copper plate), and a steel rod electrode with a tip radius ~ 1/10 inch is installed in another side of Kraft board. A steel rod electrode is connected to an impulse generator. Figure 2.14 shows the typical creeping streamer on Kraft board surface obtained under the 120 kV negative impulse voltage.

The properties of streamers travelling the surface of oil-immersed solid dielectrics also have been examined experimentally [19]. The result showed that the streamer polarity and position of a grounded side electrode significantly affected to the



**Figure 2.14** Typical photograph of creeping streamer on Kraft board surface. Applied voltage: 120 kV negative impulse voltage. [18]

relationship between streamer extension length and applied voltage. Furthermore, the charges on solid surface influenced largely to the streamer propagation. However, the properties of streamer propagation showed a consistent dependence on the potential at the solid-liquid interfaces. It has also been revealed that the potential drop inside the streamer increases drastically within the region about 20% from streamer tip. The streamer appeared progressing constantly at mean velocity.

The negative streamer developing in mineral oil has been reported [92]. A tungsten needle with the tip radius of around 1 to 30  $\mu$ m was immersed in the oil and located just above solid glass insulation. It was indicated that when the impulse high voltage was steeply applied to a needle electrode which functioned as high voltage electrode, the streamer with numerous branches was generated radially. This experiment was focused on the measurements of the mean streamer velocity, final length, electric current and charge, as the properties of streamer. From the experimental results, it has been presented that the streamer channels are not equipotential.

The main properties of creeping discharge over pressboard surface have also been investigated in mineral oil [20]. Figure 2.15 shows the creeping discharge shapes for both negative and positive needles. It is indicated that the streamer at positive needle has a lot of branches than that at negative needle. The mean electric current and the final charge demonstrate that the potential of the streamer channels is roughly the same as that of the needle electrode. Figure 2.16 shows total charge at several applied voltages.



a) Positive Needle b) Negative Needle

Figure 2.15 Typical figures of creeping discharge. [20]



Figure 2.16 Total charge at several applied voltages. [20]

From the graph, it is shown that total charge at same level of the voltage is not similar between positive and negative needles, but it is assumed that total charges between positive and negative needles are roughly the same at around 25 kV.

The investigation of creeping discharges in mineral oil has been carried out under the nanosecond high voltage pulses and the following results have been reported. The electric field strength due to discharge produced by the nanosecond high voltage pulse is higher than that produced by the AC and DC voltage or lightning surges. The electric field strength due to discharge shows its highest value as the angle between the solid insulator such as nylon 6 and polymethyl methacrylate (PMMA) and the electrode is approximately 45 °. The breakdown voltage of the solid insulator sample with the thickness in the range 1 to 3 mm is proportional to the solid insulator thickness. [24] The discharges propagating a liquid/solid interface in mineral oil have also been investigated for different samples of Bakelite insulator immersed in the oil under applied AC and DC voltages using a needle-plane electrode arrangement [96]. The associated currents and final lengths of the creeping discharge were examined experimentally as a function of the waveform and polarity of the applied voltage. The results presented that the final length of discharges increased with increasing of the voltage and decreased when a hydrostatic pressure was applied. The associated current pulses, emitted light and the number of creeping discharge branches were also reduced when the pressure was significantly increased.

At atmospheric condition, the streamer progression in mineral oil has been examined under  $1/180 \ \mu s$  impulse voltage using the needle-plane electrode geometry with gap spacing; 67 mm [28]. The streamer velocities, streamer shapes, discharge currents and light emission were measured in this experiment. The results have been obtained as follows. The velocity of the positive streamer rose gradually up to 19 km/s in maximum with the increase of voltage. The negative streamers were of a tree shape, while the positive streamers were of a bush shape. The light emission was converted to current pulses with 15 ns wide up to 10 A for both negative and positive polarities. The tips of positive streamer branches were considerably luminous than the streamer channels. This is indicating that an impact ionization phenomenon due to the electrons takes place at the tips of streamer branches.

The creeping discharge propagating the solid insulator surface in the liquids (distilled water, rain water, electrolytic aqueous solutions, mineral oil, etc.) with the parallel plane and needle-plane electrodes has been observed using the high speed schlieren equipment with a light emitting diode (LED) system which could detect pre-breakdown currents [23, 94]. This experiment which focused on the influence of arrangement of insulator barrier on streamer propagation, features of streamer, propagation mechanism of streamer and streamer velocity can combine with a current measurement. The PD activity was detected during the creeping discharge development by the conventional impulse current (CIC) signal detector at temperatures; 60 °C and 100 °C, in oil/paper insulation system [95]. It was indicated that the flashover voltage and streamer initiation voltage were much lower and the puncture breakdown of insulator barrier was also violent at 100 °C. In order to monitor the generative condition

of creeping discharges in a large capacity transformer, the correlation between leakage current measurements has also been estimated using a shunt resistor and PD signal detection.

#### 2.5.2 Investigations on Creeping Discharge in Vegetable-Based or Synthetic Oils

Although the behavior of creeping discharges in mineral oil has been investigated numerously as stated above, nowadays, the vegetable oils or synthetic oils are being watched with keen on/ interest as a substitute for mineral oil, because of an environmental problem. Therefore, the researches on the electrical insulation (including the electrical breakdown, surface flashover, partial discharges, creeping discharges etc.) in the vegetable oils or synthetic oils must also be performed as compared with those in mineral oil. In recent years, these researches in the vegetable oils or synthetic oils have been started as reviewed below.

Comparative researches to the electrical insulation properties in mineral oil have been carried out experimentally in synthetic oil and natural ester oil [21]. In these researches, the streamer initiation voltages, streamer shapes and streamer stopping length (final length) as well as the associated discharge current and charge were measured in a needle-plane electrode geometry using a standard lightning impulse voltage (1.2/50  $\mu$ s). The results showed that the streamers were filamentary in the different test oils whatever the polarity of applied voltages. The conductivity and streamer stopping lengths in natural ester oils were higher and longer than those in some mineral oils, respectively, and they were remarkable in a positive needle rather than a negative needle.

Another experiment on creeping discharges developing the pressboard (PB) surface in natural ester oils has also been carried out under AC divergent electric field. In this experiment, the commercial partial discharges detector, the wideband current measurement and the high-speed image recorder are used to measure the progression phenomena of creeping discharges. The results show that the presence of PB surface tends to promote the discharges, especially in a negative discharge, and enables more discharges to occur at smaller phase angles. It is shown that surface charges and bubble residences lead to the promotion discharge effect on the pressboard (PB) surface. This effect is more significant in esters than in mineral oil, and it is also indicated that

discharge light in ester is brighter than that in mineral oil. In this experiment, the viscosity of ester is higher than mineral oil [22].

The comparative investigation on the dielectric strength of oil/cellulose insulation for mineral oil (Lyra X) and vegetable-based oil (VBO) has also been carried out experimentally. This investigation is focused on the AC breakdown strength and insulation level (BIL) of oils. Table 2.5 presents the measured and evaluated AC breakdown values for the pressboard-cylinder model in the mineral oil (Lyra X) and vegetable-based oil (VBO). It is shown that the AC breakdown strength in mineral oil is higher than VBO. Figure 2.17 presents the breakdown values for the model with and without a paper insulated conductor in oils under the lightning impulse voltage. From the graph, it is indicated that the breakdown strength in mineral oil is higher than that in VBO for with and without the paper insulator. [93]

The behaviors of creeping streamer progressed the gap in the range 0.1 to 2.0 mm between the pressboard with a back side electrode and the acrylic resin plate have been investigated in palm fatty acid ester (PFAE) oil using  $\pm 1.2/50$  µs and  $\pm 1.2/1000$  µs lightning impulse voltages with  $\pm 140$  kV<sub>peak</sub> in maximum [25, 26]. It has been shown that the growth of positive and negative streamers depends on the spacing between two dielectrics, and it has a distinctive polarity effect on the streamer length and flashover voltage between the needle electrode and the counter electrode. On the behaviors of

Fluid	Normal Distribution					
	U <sub>1%</sub> (kV)	U <sub>50%</sub>	σ(kV)			
Lyra X	82.3	130	23.50			
VBO	45.7	98	22.79			
Fluid	Weibull Distribution					
	U <sub>1%</sub> (kV)	$U_{50\%}(kV)$ $\alpha$		β		
Lyra X	58.9	136.1	146.40	5.00		
VBO	35.7	98.8	107.89	4.15		

**Table 2.5** Measured and evaluated AC breakdown valuesfor pressboard / cylinder model in mineral oil ( Lyra X) andvegetable-based oil (VBO). [93]



**Figure 2.17** Lightning Impulse breakdown values for model with and without paper insulated conductor in oils. [93]

creeping streamers progressed in a narrow gap between two solid dielectric plates immersed in PFAE oil, it is worthy of notice that the negative streamer grows longer than the positive streamer under identical applied voltage, because this polarity effect is the inverse from that in an oil/pressboard interface without a narrow gap. The streamers in both polarities also slow down its velocity because of a narrow gap with two solid interfaces. These results on the creeping discharge have been compared with those in commercial mineral oil.

As for an interesting another research, the effect of isolated small alien substances on the creeping discharge progressing the surface of the pressboard immersed in PFAE oil has been examined experimentally, and it has been reported that the creeping streamer is largely extended by the presence of isolated small alien substances in the surface or inside of the pressboard. The effect of such alien substances also appears in the streamer shape, discharge current and streamer velocity [27].

In the synthetic and natural ester oils, streamer characteristics including the length, velocity, shape, area and mode have been investigated as well under the lightning impulse voltage at divergent field [29]. The result indicates that the streamer inception voltage in ester oils propagates faster than that in mineral oil at the same voltage level.

After the discharge inception, the streamer has a lot of branches in esters rather than in mineral oil. It is also found that fast streamer leads to breakdown at large gap from 15 mm to 100 mm in ester liquids and mineral oil under the applied lightning impulse voltage. The breakdown voltage in esters is lower than that in mineral oil.

The breakdown and streamer propagation in the synthetic and natural ester oils have been investigated experimentally using a needle-plane electrode configuration with the pressboard interface under a lightning impulse voltage [30]. The pressboard was installed in the position parallel to the electric field. This arrangement did not influence the streamer stopping length and also did not weaken the breakdown voltage at the oil gaps up to 75 mm, under both positive and negative polarities. Acceleration voltage which is gradually increased is used in this experiment, and the streamer propagation can automatically switch from slow modes (1st and 2nd) to fast modes (3rd and 4th). It is indicated that introduction of pressboard does not influence the streamer velocity in ester liquids, but significantly promotes the streamer velocity in mineral oil at overstressed voltages leading to a large reduction of acceleration voltage: about 60 kV for both 25 mm and 50 mm gap distances under the positive polarity, while under the negative polarity, the streamer velocity is accelerated at larger gap under higher voltage in both ester oils and mineral oil.

The experimental researches on breakdown voltage test in 50-150 mm gaps have been performed under the AC and standard impulse voltages. It is indicated that the mean breakdown voltage of mineral oil is slightly higher than natural ester oil at 50 mm gap, and the two oils are almost the same beyond 100 mm gap [97]. When the gap increases, the breakdown voltage under AC voltage significantly increases for the natural ester fluid. Generally, it is indicated that mineral oil is closely similar to natural ester oil in the slightly non-uniform gaps for the breakdown test under AC voltage. The lightning impulse breakdown and withstand level of natural ester oils are roughly the same with mineral oil.

The investigation on the streamer development in synthetic ester oil and natural ester oil has been carried out in comparison with that in mineral oil, using a needle-plane electrode arrangement under a standard lightning impulse voltage (with waveform of  $1.2/50 \ \mu$ s) [98]. The experiment was focused on the measurements of the streamer initiation voltage, pattern and stopping length (final length) of streamers,

discharge current and electrical charge. Consequently, it has been described that the streamers in the different test oils are filamentary whatever the polarity of applied voltages, and also the stopping length of streamers in the positive needle becomes longer than that in the negative needle. The comparative result on the streamer development in ester oils (natural and synthetic) and mineral oil presents that the streamer lengths in the ester oils are generally longer than those in some mineral oils. The stopping length of streamers in negative needle can be ten times higher in ester oils than in mineral oil.

The streamer propagation and breakdown events have been investigated using a needle to plane electrode geometry with a long gap in rapeseed oil and mineral oil [31]. The electrode gap spacing was of a large range from 2 to 20 cm and the impulse voltages up to 460 kV<sub>peak</sub> with several waveforms such as  $0.5/1400 \ \mu s$ ,  $1.2/50 \ \mu s$  and 250/2500 µs were applied to the electrode gap. The velocity of streamers progressed in oils, streamer stopping length, transient currents and charges and streak photographs of the emitted light for positive and negative streamers were measured in this experiment. Figure 2.18 shows stopping length of streamer, average velocity of streamer and streamer charge in rapeseed oil and mineral oil under positive and negative impulse voltage. From experimental results, it is shown that the stopping length of streamer, the average velocity of streamer and the streamer charge in rapeseed oil are higher than in mineral oil for both polarities of impulse voltage. It has been also shown that the several propagation "modes" can be observed in rapeseed oil with the transition from the velocity streamers of ~ 1 km/s up to 200 km/s (see Figure 2.18). Furthermore, it is presented that the propagation of the fast positive streamers occurs at much lower voltage in rapeseed oil rather than in mineral oil, which means that this induces lower breakdown voltages and shorter time to breakdown in rapeseed oil.

The electrical properties at the oil/pressboard interface with electrode gap distances of 25, 100 and 200 mm have been investigated comparatively in ester oil and mineral oil under  $1.2/50 \ \mu$ s impulse voltage [99]. The breakdown voltage and its polarity effect, streamer velocities and acceleration voltages for transition to fast event were measured experimentally. The fast event feature of streamers in ester oil is slightly different from that in mineral oil, especially at positive polarity, and the breakdown voltage values in ester oil are significantly lower than those in mineral oil over long electrode gaps.

Furthermore, the transition voltages to fast event in mineral oil are much larger than those in ester oil, and the streamer velocity at fast event in ester oil rises much more steeply at over-voltages than that in mineral oil. Streamer velocity has been recorded up to 120 km/s.



**Figure 2.18** a) Stopping length of streamer, b) average velocity of streamer and c) streamer charge in rapeseed oil under positive and negative impulse voltage ( $V_b$  : 50% probability breakdown voltage,  $V_a$ : acceleration voltage, d = 10 cm gap distance) [31] Broken lines are comparison with mineral oil.

The investigation on creeping discharges over the pressboard surface in rapeseed ester oil, mineral oil and silicone oil has been carried out under standard lightning impulse voltage conditions [100]. The basic discharge properties such as discharge shape, streamer length, discharge current and charge on the creeping streamer propagating from a needle electrode were measured in this investigation. The result indicated that rapeseed ester oil has a high insulating strength. By using a high-speed image converter camera (ICC), the barrier effect on the propagation of creeping streamer propagation velocity was significantly affected by the barrier.

The electrical properties of natural ester oil and mineral oil have been compared by the lightning impulse test, and it is shown that the natural ester oil has the performance of roughly the same level as mineral oil [32]. The testing procedures may have caused an air bubble entrapment in the natural ester oil with a higher viscosity. Before investigation, the gases trapped in the natural ester oil should be reduced by a vacuum pump, and also a lower viscosity for improving the heat transfer and removal of the particulates and dissolved gas should be maintained.

The experimental investigations on the creeping discharge pattern and the accompanying the treeing processes on the pressboard surface have been reported in synthetic and natural ester oils [101]. In this investigation, the fast digital video recorder, wideband discharge current sampling resistor and commercial PD detector are used as the tool and equipment. It is found that the intense discharges occurring on/near the pressboard surface lead to the erosion of the pressboard surface. After creeping discharges evaporate the oil and moisture, the white mark can be seemed clearly on the pressboard surface. Because of this white mark, the creeping discharge can easily develop on the pressboard surface in the gap between high voltage electrode and ground electrode at a level voltage. When creeping discharge may close to ground electrode, it will finally lead to flashover.

As another investigation on the vegetable-based oil, the electric field strength between the parallel-plate electrodes in PFAE oil has been measured using the Kerr electro-optic technique under various PFAE conditions (PFAE at rest (without flow) / uncharged PFAE with flow / charged PFAE with flow), and the results have been compared with those in mineral oil as follows [102]:

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- 1. The flow rate of oil and the leakage current showed a linear relationship in PFAE oil and the charge density in oil was ~  $0.8 \text{ pC/mm}^3$  at 14 *l*/min.
- Electric field strengths in a PFAE oil gap went down versus time and were not influenced by the flow of charged oil, while the influence of charged oil flow on electric field was clearly displayed in mineral oil.
- 3. The ion density between two oils revealed elegantly distinctive characteristics, so that the ion density of PFAE oil was much higher than that in mineral oil.

Furthermore, the electric field distributions and their time variation in rapeseed ester oil with a parallel-plate electrode and in the rapeseed ester oil/pressboard (PB) composite insulation systems have been measured using the Kerr electro-optic technique under DC voltage application in both uncharged and charged oils with flow. It is notable that the electric field distortion in the oil charged by flow electrification can be quantitatively clarified in this research. The measurements of the leakage current and a charge density distribution along the flow direction have also been carried out using divided electrodes. Main results are summarized as follows [33-34]:

- 1. The values of Kerr constant of rapeseed ester oil and mineral oil at room temperature were measured as  $2.04 \times 10^{-16}$  m/V<sup>2</sup>,  $2.25 \times 10^{-15}$  m/V<sup>2</sup>, respectively. Kerr constant of mineral oil was approximately one order larger than rapeseed ester oil.
- 2. The time variation of the electric field strength in rapeseed ester oil was roughly the same as that in mineral oil for the parallel-plate electrode oil gap.
- 3. The electric field strength went down with time in the rapeseed ester oil / PB composite system. This was attributed to the space charge in the oil accumulated on the oil/PB interface. The electric field strength in the mineral oil was larger than that in rapeseed ester oil.

#### 2.6 DISSOLVED GAS-IN-OIL ANALYSIS (DGA) IN OILS

Dissolved gas-in-oil analysis (DGA) is the way to identify several gases dissolved in the oil inside the power transformer after fault events such as arcing, partial discharge (PD), low and high energy discharges, overheating of oil or paper insulations etc. A DGA technique has widely been adopted as a fault indication in the power transformer since 1960. Generally, the following nine gases are examined as a fault gas [84]:

Subject of components	Carrier gas	Analysis column	Detector	Injection rate [mL]	Extraction time [s]
Hydrocarbon (C1 ~ C2)	Nitrogen	Porapak + activated	FID	1	120
Hydrocarbon (C1 ~ C2) CO, CO2	Nitrogen	Activated carbon	FID	1	120
Hydrogen	Nitrogen	Molecular sieve	TCD	1	120
Oxygen, Nitrogen	Helium	Molecular sieve	TCD	1	120

**Table 2.6** Extraction and detection of gases in DGA system. [103]



Figure 2.19 Schematic diagram of DGA process. [103]

- 1. Atmospheric gases: hydrogen (H), nitrogen  $(N_2)$  and oxygen  $(O_2)$
- 2. Oxides of carbon: carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>)
- 3. Hydrocarbons: acetylene ( $C_2H_2$ ), ethylene ( $C_2H_4$ ), methane ( $CH_4$ ) and ethane ( $C_2H_6$ ).

The extracting or stripping the gases from the oils (vegetable oils and mineral oil) and injecting them into a gas chromatograph (GC) are involved in a DGA technique. Detection of gas concentrations usually is carried out by using a flame ionization detector (FID) and a thermal conductivity detector (TCD). The extraction and detection of gases in DGA system are shown in Table 2.6. Figure 2.19 shows the schematic diagram of DGA process [103].

There are some theories such as Duval triangle, the Electric Technology Research Association (ETRA) method, IEC ratio and Roger ratio on the interpretation of the DGA. Duval's schematic method is diagnosed by applying to the Duval triangle the data obtained from the three key gases; acetylene ( $C_2H_2$ ), ethylene ( $C_2H_4$ ) and methane

(CH<sub>4</sub>), extracted from small volume of transformer oil and the following three equations normalized to 100% [35-36, 63].

$$\%C_{2}H_{2} = \frac{100x}{x+y+z}; \quad x = [C_{2}H_{2}] \text{ in ppm .....(13)}$$
$$\%C_{2}H_{4} = \frac{100y}{x+y+z}; \quad y = [C_{2}H_{4}] \text{ in ppm .....(14)}$$
$$\%CH_{4} = \frac{100z}{x+y+z}; \quad z = [CH_{4}] \text{ in ppm .....(15)}$$

The kind of fault in the power transformer such as partial discharge (PD), low energy discharge (D1), high energy discharge (D2), heat failure for temperature range t < 300 °C (T1), heat failure for temperature range 300 °C < t < 700 °C (T2) and heat failure for temperature range t > 700 °C (T3) is classified by the Duval triangle [85-87]. Figure 2.20 shows the Duval triangle used for a fault diagnosis in power transformers.

The criterion of gases limitation (L1) and generation rate (G1 and G2) in power transformer can be determined by using Table 2.7. The limitation and generation of total combustible gases usually refer to L1 and G2, respectively [130].

According to the report of the Electric Technology Research Association (ETRA) in Japan on "The maintenance control of oil-filled transformer", the maintenance is based on the dissolved gas analysis of insulation. The discharge mode and overheating



Figure 2.20 Duval triangle indicating fault in power transformer. [35-36, 63]

		G1 Limits	G2 Limits
Gas	L1 Limits	(ppm per month)	(ppm per month)
$H_2$	100	10	50
$\mathrm{CH}_4$	75	8	38
$C_2H_2$	3	3	3
$C_2H_4$	75	8	38
$C_2H_6$	75	8	38
CO	700	70	350
$CO_2$	7,000	700	3,500

**Table 2.7**Limitation (L1) and generation rate (G1 and G2) in DGA. [130]

mode can be emphasized by the ETRA diagnostic method. However, it is difficult to distinguish between the abnormality of an iron core and a winding group in the overheating mode. The diagnostic method in the ETRA standard may vary a precision improvement of the overheating point inside the transformer [37, 64, 104-105].

The ETRA standard basically is selecting six kinds of combustible gases;  $H_2$ ,  $CH_4$ ,  $C_2H_6$ ,  $C_2H_4$ ,  $C_2H_2$  and CO. Table 2.8 represents the limitation of total combustible gases for every level. Figure 2.21 shows the graphs of a percentage gas ratio ( $C_2H_6/C_2H_4$  or

JUDGEMENT				CON	TENT		
LEVEL							
						unit	in ppm
Warning	TCG	$H_2$	$CH_4$	$C_2H_6$	$C_2H_4$	$C_2H_2$	СО
Level I	500	400	100	150	10	0.5	300
	One of	them ex	ceeds th	e level.			
	When C	$C_2H_2 >$	0.5ppm	, the lev	el will b	e the W	arning Level II
Warning							
Level II	② $C_2H_4 \ge 10$ ppm and TCG $\ge 500$ ppm						
	① C <sub>2</sub>	$H_2 \ge 5$	ppm o	or			
Trouble	② C <sub>2</sub>	$H_4 \ge 1$	00ppm	and TCC	G ≧ 70	0ppm	or
Level	③ C <sub>2</sub>	$H_4 \ge 1$	00ppm	and incr	ement T	CG ≧	70ppm/month

 Table 2.8
 ETRA assessment for DGA in oil-filled power transformer. [64]



**Figure 2.21** Electric technology research association (ETRA) standard in diagnosis of power transformer. (a) ETRA Type A and (b) ETRA Type B. [64]



**Figure 2.22** Flowchart of ETRA standard for DGA in power transformer. [104]

 $C_2H_2/C_2H_4$ ) grouping the kind of failure (discharge, superheat, superheat+discharge etc.). Figure 2.22 shows the flowchart of the ETRA standard for the DGA in power transformers.

Table 2.9 shows the IEC ratio for some faults in the power transformer predicted by comparison between  $C_2H_2/C_2H_4$ ,  $CH_4/H_2$  and  $C_2H_4/C_2H_6$ , and it has the differences between other standards. The methods to analyze dissolved gases in the power transformer have been explained in the IEC 60567 standard [38, 65, 106].

Nature of the fault	$C_2H_2/C_2H_4$	$CH_4/H_2$	$C_2H_4/C_2H_6$
Partial Discharge (PD)	NS	< 0.1	< 0.2
Low energy discharges (D1)	>1	0.1 - 0.5	> 1
High energy discharges (D2)	0.5 - 2.5	0.1 - 1	> 2
Low thermal fault T °C (T1)	NS	> 1	< 1
Medium thermal fault T °C (T2)	< 0.1	> 1	1 - 4
High thermal fault T °C (T3)	0.2	> 1	>4

**Table 2.9**Interpretation of DGA according to IEC ratios. [38]

Ratio Code	Range	Code
i	$ratio \leq 0.1$	5
	0.1 < <i>ratio</i> < 1.0	0
	$1.0 \leq ratio < 3.0$	1
	$ratio \ge 3.0$	2
j	<i>ratio</i> < 1.0	0
	$ratio \ge 1.0$	1
k	<i>ratio</i> < 1.0	0
	$1.0 \leq ratio < 3.0$	1
	$ratio \ge 3.0$	2
1	<i>ratio</i> < 0.5	0
	$0.5 \leq ratio < 3.0$	1
	$ratio \geq 3.0$	2

Table 2.10Roger ratio code. [107]

i	j	k	1	Diagnosis	
0	0	0	0	Normal deterioration	
5	0	0	0	Partial discharge	
1-2	0	0	0	Slight overheating	
				< 150 °C	
1-2	1	0	0	Overheating	
				$150^{0}C - 200 \ ^{\circ}C$	
0	1	0	0	Overheating	
				$200^{0}$ C - 300 °C	
0	0	1	0	General conductor overheating	
1	0	1	0	Winding circulating currents	
1	0	2	0	Core and tank circulating currents,	
				overheated joints	
0	0	0	1	Flashover without power follow through	
0	0	1-2	1-2	Arc with power follow through	
0	0	2	2	Continuous sparking to floating potential	
5	0	0	1-2	Partial discharge with tracking (Note CO)	

 Table 2.11
 Kind of faults based on Roger ratio code. [107]

In the Roger ratio method, there are four comparisons to explain dissolved gases such as  $CH_4/H_2$ ,  $C_2H_4/C_2H_6$ ,  $C_2H_6/CH_4$  and  $C_2H_2/C_2H_4$ . This method analyses the faults by a ratio code (i =  $CH_4/H_2$ , j =  $C_2H_6/CH_4$ , k =  $C_2H_4/C_2H_6$ , and l =  $C_2H_2/C_2H_4$ ), and then the combination code identifies the kind of fault in power transformer. Table 2.10 and Table 2.11 show the ratio code and kind of fault [107].

Generally, the C-H molecular bonds are created or decomposed at low temperatures or energy, and high temperatures or energy are necessary to produce or decompose the C-C single bonds, C=C double bonds and C=C triple bonds. The creation of gases depends on the temperature, and the fault gases are generated in the order of  $H_2 \rightarrow CH_4 \rightarrow C_2H_6 \rightarrow C_2H_4 \rightarrow C_2H_2$  with an increase of temperature.  $H_2$  gas is detected at the temperature in the range of 100 to 150 °C. CH<sub>4</sub> and C<sub>2</sub>H<sub>6</sub> gases with the C-H and C-C single bonds respectively can be formed at the temperature in the range of 250 to 350 °C. C<sub>2</sub>H<sub>4</sub> gas with C=C double bond can also be formed at higher temperature in the range of 200 to 500 °C. The formation of C<sub>2</sub>H<sub>2</sub> with C=C triple bond starts at the temperature exceeding 500 °C (usually 500 to 700 °C) [40-41].

### 2.7 OPTICAL MEASUREMENTS OF DISCHARGE CURRENT USING LED

The partial discharge (PD) pulse can be measured by using a current transformer (CT). However, generally there are many electrical noises from a high voltage generator that is the disturbance in current measurements. In order to solving this problem, the current pulse measurement system using the optical fibers, light emitting diode (LED), photomultiplier (PMT) or photodetector, amplifier, and digital oscilloscope has been developed [42-44].



(a) Current measurement circuit for impulse voltage



(b) Current measurement circuit with antiparallel LED for AC voltage.

Figure 2.23 Basic circuits of optical current measurement using LED. [42]

Figure 2.23 (a) and (b) present the basic circuits of the optical current measurement using LED. When an electrical energy is released through the system as shown in Figure 2.23 by an impulse generator or AC test transformer, the pulsative currents flow the system and then the LED will emit the light. This light is guided via an optical fiber to a photodetector or photomultiplier tube (PMT), and it is transferred to input current pulses which are detected by a digital oscilloscope. The advantages for the use of this system are as follows:

- 1. The systems will be less electrical noise from the signal system.
- 2. The optical fiber in the systems functions as an electrical insulator between LED and PMT. Therefore, even though the LED is destroyed by the overcurrent due to the accident such as breakdown or flashover, the digital oscilloscope will not be damaged.
- **3.** By the use of the circuit in Figure 2.23 (b) for the measurements of the creeping discharge currents under applied AC voltage, the current flowing at a half cycle in positive and negative polarities of AC voltage can be detected by two LEDs in a reversed parallel connection, respectively.

### 2.8 AGING OF VEGETABLE-BASED OIL INSULATION

Power transformers including the insulation materials such as oil as liquid insulator and paper and pressboard as solid insulator are essential apparatus in an electric power system. The life of power transformer is limited critically by the degradation of insulation materials that related to the electric breakdown strength of insulators. In order to evaluate the degradation of tensile strength in solid insulators (kraft paper, pressboard, wood etc.), the degree of polymerization (DP) is widely implemented as a basic evaluation [45]. Polymer molecule (for example, polymer molecule A) may be represented by the chemical formula of the following type [66],

 $A^{-}A - A - A - A^{-} \cdots - A^{-} or A^{-} (-A - )_{x} - A^{-}$ 

where the principal chemical structural unit (repeat unit) is represented by molecule A, and x denotes the degree of polymerization (DP) which can examine the deterioration in insulations by calculating the number of repeat unit in a macromolecule or polymer molecule. The degree of polymerization (DP) is given by the mathematics formula as follows [66]:

where  $M_n$  denotes the molecular weight of polymer (for example, polymer molecule A) and  $M_0$  the molecular weight of the repeat unit of molecule A.

The investigation on the vegetable-based oils as a substitution of mineral oil has also been done for the sample oils aged by heating and the electric breakdown strength of the aging vegetable oil (Bioterm) has been compared with the aging mineral oil. Before the experiment, the sample oils are put into a heating oven at 90 °C for several days (see Figure 2.22). The breakdown strength tests were carried out after the sample oils were taken from the oven and put at room temperature for 24 hours. Figure 2.24 shows the breakdown strength of the mineral oil and vegetable oil (Bioterm) aged at 90 °C. It is shown that the vegetable oil (Bioterm) keeps roughly the breakdown strength of 24 kV/mm, while the mineral oil varies between 10 kV/mm and 20 kV/mm at same aging time. It is also indicated that the breakdown strength in vegetable oil is higher than that in mineral oil [47].

Molecular modeling analysis for vegetable oil's ability to retard the rate of degradation has also been studied in comparison with mineral oil. This physicochemical model explained the interaction between the paper insulation (solid insulation) and the liquid insulation (mineral oil and vegetable oil). The water molecule was added in the insulation system by 5 wt% and the simulation was done at the temperature of 383 K (110  $^{\circ}$ C). The simulation result has demonstrated that the paper insulator in the



Figure 2.24 Breakdown strength of insulating oil at 90 °C aging. [47]

vegetable oil has larger activation energy and the natural ester is easy to interact with water molecules. Mineral oil can contain a little water rather than the vegetable oil, and the aging rate of paper immersed in mineral oil is faster than the vegetable oil [47].

The influence of moisture content on the aging performance in natural ester oil/paper insulation system has been investigated in comparison with that in mineral oil-paper insulation system. The results indicate that the aging of insulating paper in both natural ester and mineral oil can be accelerated by the moisture content, and the degradation rate of insulating paper in mineral oil is much higher than that in natural ester oil [111].

An air reaction of vegetable oils leads to the aging such as oxidation and strong increase of viscosity. Therefore, transformers filled these oils need to seal a container hermetically. In the past investigations, the vegetable oils to be suitable in power transformer use have been pointed out. For instance, the degree of polymerization (DP) in the natural esters (FR3, MeN, Hoso), synthetic ester (M7131) and mineral oil (Nynas) have been tested. The result of analysis was dependent on closed and opened conditions of the chamber. As reference result, the original status (Orig.) with DP = 715 indicates that the aged samples has clearly deteriorated. Figure 2.25 shows that the DP in aged samples of synthetic ester (M7131) and mineral oil (Nynas) are lower than that of the natural esters (FR3, MeN, Hoso). It has also been reported that the natural esters have better behavior than mineral oil concerning the paper aging [48].

Figure 2.26 shows the dielectric loss as a function of aging time for oils (dodecyl-benzene (DDB), Enviroterm and several vegetable oils) aged at 135 °C with



Figure 2.25 Degree of polymerization of paper after aging. [48]

copper. It is indicated that Enviroterm and yellow olive oils are lower dielectric loss at 135 °C than DDB and other vegetable oils at same aging time.

Figure 2.27 shows the relation between the viscosity and aging time for oils (sunflower oil, rapeseed oil, DDB and Enviroterm) aged at 120 °C with copper. From this figure, it is indicated that Enviroterm and DDB are lower viscosity at 120 °C than other vegetable oils at the same aging time. Enviroterm also has excellent oxidation stability [46].



**Figure 2.26** Dielectric loss as a function of aging time for oils aged at 135 °C with copper. [46]



**Figure 2.27** Viscosity against aging time for oils aged at 120 °C with copper [46].



**Figure 2.28** Degree of polymerization of thermally upgraded Kraft at various temperatures normalized to IEEE unit life for 200 DP. [110]

Figure 2.28 shows the decrease in degree of polymerization (DP) of the natural ester/thermally upgraded Kraft and mineral oil/thermally upgraded Kraft insulation systems aged in sealed tubes. It is indicated that the natural ester/Kraft insulation system presents a similar decrease in aging rate with mineral oil/Kraft insulation system. Degrees of polymerization (DP) of natural ester were higher than those of mineral oil at several temperature levels.

Although the creeping discharge and flashover phenomena on the aging mineral oil/pressboard interface have been reported until now, there are only a few reports for these phenomena on the aging vegetable-based oil/pressboard interface. Therefore, the undermentioned research will be restricted to the phenomena in the aging mineral oil for the present. The investigation on the AC creeping discharge on the aging mineral oil/pressboard interface has been done experimentally. It is indicated that the introducing a dry new pressboard into the mineral oil will increase the flashover voltage, and also the introducing an aged pressboard with moisture contents up to 3% do not significantly reduce the breakdown voltage caused by a single flashover. Furthermore, the increase of moisture content in the pressboard significantly reduces the PD inception voltage (reduction of approximately 30 %). The high moisture contents in pressboard significantly strengthen PD activities in oil pores, which be decay oil molecules to be gasses and these gasses will be trapped inside pressboard to develop gaseous channels.

The creeping discharge will progress inside these channels until breakdown event [49].

The flashover process over the mineral oil/paper interface has also been investigated using four oil/pressboard specimens with different aging degrees, and it has been indicated that the maximum charge and frequency in a pulsative waveform of partial discharges (PD) sharply rise with the increase of applied voltage. The PD characteristic at the oil/pressboard interface is influenced greatly by the aging of oil rather than the aging of pressboard. The PD pattern and waveform of current pulses have the large differences for various applied voltages. In this experiment, it is suggested that the PD detection in the oil/pressboard insulation system can be applied effectively to monitor early the creeping discharge and to avoid the formation of surface flashover [50].

# **CHAPTER III**

# DISSOLVED GAS-IN-OIL ANALYSIS (DGA) TEST IN VEGETABLE-BASED OIL [113, 119] (Influence of Various Discharges)

## 3.1 OBJECTIVE OF RESEARCHING

Mineral oils have most often been used as a dielectric liquid in oil-filled power apparatuses over more than a century, because of their high performance as electrical insulation and thermal coolant. However, several disadvantages such as poor biodegradation, low flash point, low relative permittivity, slight toxic, exhaustion of mineral resources, sulfide-induced corrosion of copper, environmental pollution due to oil leakage and atmospheric pollution due to burning have been pointed out for practical use of mineral oils. Recently, the environmentally inoffensive vegetable-based oils are considered as a substitute of mineral oil. On the other hand, since an analytic technique of the gases dissolved in mineral oils make the diagnosis of power transformers possible, the component of gases is measured to evaluate a feature of faults in transformers [67]. These gas analysis data are also important to examine the some mechanisms of faults. The technique of diagnosis based on the gas analysis, however, has not been established until for new power apparatuses utilized vegetable-based oils. We must grasp the component of gases dissolved in vegetable-based oils to develop the diagnostic method for new power apparatuses under various conditions.

The aim of this research is to clarify the component of gases dissolved in natural rapeseed oil by several discharges (impulse arc discharge, AC creeping discharge, corona discharge, etc.), and to indicate the results of diagnostic evaluation based on a dissolved gas-in-oil analysis (DGA) in comparison with mineral oil. The experimental set up and method of the DGA are presented in this section. The relations between the amount and the components of dissolved gasses after the discharge treatment are clarified in rapeseed oil and mineral oil. The failure modes based on the DGA results after the discharge treatment have been diagnosed from the Electric Technology

Research Association (ETRA) criterion and the International Electro-technical Commission (IEC) criterion using the Duval Triangle.

#### 3.2 EXPERIMENTS ON DGA IN OILS UNDER CORONA

#### **3.2.1** Experimental Setup and Procedure

Figure 3.1 shows the schematic of the test setup used to generate an arc discharge in the oil under the impulse high voltage. The test vessel was a cylindrical type made of transparent acrylic resin. The test vessel was a cylindrical type made of transparent acrylic resin. A needle to plane electrode system with the gap spacing  $\Delta D = 10$  mm was installed inside the test vessel as shown in Fig. 3.1. In order to avoid the oxidation of oil or the invasion of impurities such as moisture and other gases, the sample oil (500 cc) required in one try of the dissolved gas analysis was introduced after the test vessel was filled with gaseous nitrogen (GN<sub>2</sub>) with 99.999 % purity using a vacuum pump and it was closed up tightly. The needle electrode was tungsten wire of 0.5 mm in diameter with a tip radius of ~ 30 µm and it was used as the high voltage electrode. The plane electrode was the grounded Rogowski type made of stainless steel with 50 mm in diameter and 10 mm in thickness. A standard lightning impulse voltage (1.2/50 µs) with peak value ±140 kV was applied to the needle electrode. Then, the arc



Figure 3.1 Schematic of DGA test setup for impulse arc discharge in oil.

discharge occurred at the gap between electrodes in the sample oil. In this research, the analysis of dissolved gases was conducted for 10, 30 and 50 trials of the discharge. Each impulse voltage was applied at ~ 5 minute intervals. The voltage waveform was monitored by a digital oscilloscope (Tektronix Inc.) through the high voltage probe. And the discharge current was also measured with an oscilloscope using the current transformer connected through the plane electrode. The energy  $W_{BD}$  consumed by the arc discharge was estimated from the applied voltage and discharge current.

Figure 3.2 shows the schematic of test setup used to generate an AC corona discharge in the oil. The test vessel was of the same type as that shown in Fig. 3.1, and a needle to plane electrode system was also used. In this case, in order to avoid the complete breakdown between electrodes, a glass barrier (TEMPAX) with 3.2 mm in thickness was installed on the plane electrode as shown in Fig. 3.2. This glass barrier contributes to the generation of a stable corona discharge at the needle tip. The gap spacing between the needle tip and the glass barrier surface was 10 mm. The corona discharge in the sample oil was generated by applying the 60 Hz AC voltage with 38 kV<sub>rms</sub> (root-mean-square) to the needle electrode. The plane electrode was grounded through 1  $\mu$ F capacitor. The electric power consumed by the discharge was measured by calculating the area of a *V-Q* Lissajous diagram taken from the applied



Figure 3.2 Schematic of DGA test setup for AC corona discharge.

voltage V divided by a high voltage probe and the electric charge Q of 1  $\mu$ F capacitor using a Sawyer-Tower circuit. The Lissajous figure was created in the amount of charge Q and voltage V for one cycle. The analysis of dissolved gases was conducted for 15 minutes, 30 minutes and 60 minutes of the discharge.

All experiments were performed at room temperature in the atmospheric pressure.

#### 3.2.2 Analytical Method of Dissolved Gas in Oils

Generally, the dissolved gas-in-oil analysis (DGA) has widely been used to estimate a feature of faults in oil-filled transformers [40, 51, 63]. The component of gases dissolved in sample oils was examined at Kanden Engineering Corporation in Japan by means of the gas chromatograph (GC). Figure 3.3 depicts the schematic of the gas analysis system in oils and the conditions of measurement are presented in Table 3.1. The component of dissolved gases was detected by introducing directly the gases dissolved in sample oil to the GC using the stripping extraction method which was done by the carrier gas itself bubbling through a small volume of the oil sample [63]. The extraction was controlled by turning the six port valves.



Figure 3.3 Schematic of gas analysis system in sample oils.

Subject of components	Carrier gas	Analytic colmn	Detector	Injection rate (mL)	Extraction time (s)
Hydrocarbon (C1 - C2)	Nitrogen	Porapak+ Activated alumina	FID	1.0	120
Hydrocarbon (C1 - C2), CO, CO2	Nitrogen	Activated carbon	FID	1.0	120
Hydrogen	Nitrogen	Molecular sieve	TCD	1.0	120
Oxygen, Nitrogen	Helium	Molecular sieve	TCD	1.0	120

**Table 3.1**Conditions in measurement of dissolved gasses.

\*The separated CO and CO<sub>2</sub> were measured via a methanation reaction using restoration colmn (methanizer). \*FID: Flame ionization detector, \*TCD: Thermal conductivity detection

# 3.3 EXPERIMENTAL RESULTS AND DISCUSSION

# 3.3.1 Dissolved Gas-in-Oil Analysis (DGA) under Impulse Voltage in Rapeseed Oil [113]

## [A] Arc discharge and discharge energy

Figure 3.4 shows the typical example of the positive impulse arc discharge in rapeseed oil. The arc discharge emitted an intensive light with a loud noise in both



Figure 3.4 Impulse arc discharge in rapeseed oil.

**Table 3.2** Energy  $W_{BD}$  consumed by arc discharge.

	Discharge energy $W_{BD}$ [J]			
	Positive	Negative		
Rapeseed oil	~ 170	~ 269		
Mineral oil	~ 237	~ 262		
rapeseed oil and mineral oil for the polarities of impulse voltage. The energy  $W_{BD}$  consumed by the arc discharge is shown in Table 3.2. In both oils, the  $W_{BD}$  in positive impulse voltage was smaller than that in negative one, especially its difference was large in rapeseed oil.

#### [B] Analysis of gasses dissolved in oils

Figure 3.5 shows the relation between the amount of dissolved gasses and the components of gasses after the arc discharge treatment. Figure 3.6 shows the relation between the amount of gases ( $CH_4+C_2H_4+C_3H_8$ ) and the number of discharge  $N_A$ . The following features are found from these results on dissolved gasses.

(1) A great amount of acetylene gas (C<sub>2</sub>H<sub>2</sub>) was detected in both the discharge treated rapeseed oil and mineral oil.



Figure 3.5 Relation between amount of dissolved gasses and components of gasses.



**Figure 3.6** Relation between amount of gases  $(CH_4+C_2H_4+C_3H_8)$  and number of discharge  $N_A$ .

- (2) Rapeseed oil dissolved much more carbon monoxide gas (CO) than mineral oil.
- (3) Dissolved gasses such as methane (CH<sub>4</sub>), ethylene (C<sub>2</sub>H<sub>4</sub>) and propane (C<sub>3</sub>H<sub>8</sub>) depended on the polarities of applied voltage and a sort of oils. It is shown that the gasses dissolved in rapeseed oil under the positive discharge for detectable gasses such as CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub> and C<sub>3</sub>H<sub>8</sub> were higher than under the negative discharge. Furthermore, it is relevant to a large difference between the positive and negative discharges base on the energy consumed by the arc discharge. However, in mineral oil, the amounts of these gasses for the negative discharge exceeded slightly those for the positive discharge.
- (4) The amount of  $CH_4+C_2H_4+C_3H_8$  in both oils increased with increasing the number of discharge  $N_A$ , whereas hydrogen (H<sub>2</sub>) gas had a tendency to decrease by the increase of the  $N_A$ .

#### 3. 3.2 Diagnosis after Arc Discharge Treatment

#### (i) DGA diagnostic method based on ETRA

One diagnostic method in the dissolved gas-in-oil analysis (DGA) has been standardized by the Electric Technology Research Association (ETRA). The diagnostic charts obtained from the gas analysis in this research are shown in Figure 3.7 according to the method of ETRA. The "Diagnosis A" in Figure 3.7 is diagnosed as "Discharge" and the "Diagnosis B" is diagnosed as "High-energy discharge". From these results, it can be diagnosed that the impulse arc discharge in rapeseed oil and mineral oil is roughly the same in both oils.



Figure 3.7 Diagnostic charts obtained from the gas analysis (ETRA criterion).





Figure 3.8 Diagnostic chart in Duval triangle (IEC criterion).

Another diagnostic method in the DGA has been standardized by the International Electro-technical Commission (IEC) using the Duval Triangle. Figure 3.8 shows the diagnostic chart in the Duval Triangle. In this diagnostic method, the plots of data obtained by the gas analysis belong to the region D1 of "Low-energy discharge" which is diagnosed similarly in both rapeseed oil and mineral oil.

#### (iii) Comparison between diagnostic results in ETRA and IEC standards

The diagnostic result in the ETRA obtained from the gas analysis in this research was different from that in the IEC. It is thought that the distinction between the diagnostic results in the ETRA and IEC is due to a difference of the point of view between the ETRA and IEC on the ratio of gas generation and the discharge phenomena. In this research, the diagnostic chart in the Duval triangle indicated "Low-energy discharge" in spite of the impulse discharge with a form of arc. It seems that the criterion of diagnosis in the IEC has been set generously up than that in the ETRA.

## 3.3.3 Dissolved Gas-in-Oil Analysis in Rapeseed Oil under Corona Discharge [119]

The dissolved gas-in-oil analysis (DGA) in oil under corona is one of fault diagnostic in power transformer with identifying dissolved gas in oil caused by corona. In this experiment, the DGA was carried out for comparison between mineral oil and rapeseed oil, and six types of gas used gas analysis in oil such as methane (CH<sub>4</sub>), ethane (C<sub>2</sub>H<sub>6</sub>), ethylene (C<sub>2</sub> H<sub>4</sub>), acetylene (C<sub>2</sub>H<sub>2</sub>), hydrogen (H<sub>2</sub>) and carbon monoxide (CO). It is also measure the discharge energy (dissipation energy) by sawyer-tower circuit for both oils. DGA analysis is the most widely used method for maintenance of power transformers insulated with mineral, silicone oils and synthetic ester oils.

Figure 3.9 and 3.10 are Lissajous graph for mineral oil and rapeseed oil respectively. Discharge power  $J_i$  is calculated by the formula (17) in chapter V where  $V_s$  denotes the discharge sustaining voltage of 38 kV in rms, f the frequency of applied voltage of 60 Hz, m the voltage dividing ratio of 5000 and S the area of the Lissajous graph. Result of the calculation is 0.33 W in mineral oil while it is 0.30 W in rapeseed oil. Discharge power in both mineral oil and rapeseed oil can be seen approximately equal.



Figure 3.9 Lissajous diagram of mineral oil (38 kV, after 30 min.)



Figure 3.10 Lissajous diagram of rapeseed oil (38 kV, after 30 min.)

rai oli. JUnit: p	pm			
Component of Time of Discharge (minute)				
DGA	60			
H <sub>2</sub>	5	5	5	
$CH_4$	1	4	7	
C <sub>2</sub> H <sub>6</sub>	<1	3	6	
$C_2H_4$	2	6	12	
$C_2H_2$	3	10	20	
СО	2	3	3	
Total Gas	14	31	53	

**Table 3.3**Oil-in-gas analysis result after discharge ofmineral oil. [Unit: ppm]

Component of	Time of Discharge (minute)				
DGA	15	30	60		
H <sub>2</sub>	6	12	6		
$CH_4$	1	6	20		
$C_2H_6$	3	4	8		
$C_2H_4$	<1	4	34		
$C_2H_2$	6	20	106		
СО	6	9	28		
Total Gas	23	55	202		

**Table 3.4**Oil-in-gas analysis result after discharge ofrapeseed oil. [Unit: ppm]

Table 3.3 and 3.4 show the results of a gas-in-oil analysis after the discharge in mineral oil under AC voltage of 38 kV<sub>rms</sub> and the amount of gas components for 15, 30 and 60 minutes trials, respectively. It is shown that the total combustible gas in rapeseed oil is higher than in mineral oil for 15 minutes, 30 minutes and 60 minutes, respectively.

Figure 3.11 presents acetylene generation rate versus time variation in both rapeseed oil and mineral oil. It is also shown that acetylene gas in rapeseed oil is much larger than in mineral oil within 60 minutes trial.



**Figure 3.11** Acetylene generation rate versus time variation in both rapeseed oil and mineral oil.

Figure 3.12 shows the amount of gas generated in mineral oil versus time variation.

From this graph, hydrogen (H<sub>2</sub>) is remain stable while methane (CH<sub>4</sub>), ethane (C<sub>2</sub>H<sub>6</sub>), ethylene (C<sub>2</sub>H<sub>4</sub>), acetylene (C<sub>2</sub>H<sub>2</sub>) slightly increased for 15 minutes, 30 minutes and 60 minutes trials respectively. However carbon monoxide (CO) for 15 and 30 minutes slightly rose whereas for 60 minutes, it was slightly down.



Figure 3.12 Amount of gas generated in mineral oil versus time variation.

Figure 3.13 presents the amount of gas generated in rapeseed oil versus time variation. Methane (CH<sub>4</sub>), ethane (C<sub>2</sub>H<sub>6</sub>), ethylene (C<sub>2</sub>H<sub>4</sub>), acetylene (C<sub>2</sub>H<sub>2</sub>) slightly increased for 15 minutes and 30 minutes trials, respectively, while for 60 minutes trial, these gases largely increased and they were also higher than in mineral oil. On the other hand, hydrogen (H<sub>2</sub>) slightly rose for 15 minutes and 30 minutes test respectively, whereas for 60 minutes test, this gas slightly decreased.



Figure 3.13 Amount of gas generated in rapeseed oil versus time variation.

#### **3.3.4** Diagnostic Results of Gas Composition Ratio (ETRA A and B)

ETRA has determined the composition ratio of the abnormality diagnosis in oil insulation and diagnostic method according to the composition ratio as mentioned in Chapter 2 such as abnormal diagnostic diagram in the ETRA A is  $(C_2H_2/C_2H_4 - C_2H_4/C_2H_6)$  while in the ETRA B  $(C_2H_2/C_2H_6 - C_2H_4/C_2H_6)$ . The kind of fault is determined by diagnostic diagram (Figure 3.14) where the data were obtained from the results of Table 3.5 and 3.6 for mineral oil and rapeseed oil, respectively. We can also see in Table 3.5 and 3.6 the composition ratio of the amount of gas generated in mineral oil and rapeseed oil.

The result of the abnormality diagnosis ETRA A, as Figure 3.14(a), both of oils are diagnosed as "discharge" while the result of the abnormality diagnosis ETRA B, as Figure 3.14(b), it is diagnosed the "medium energy discharge", furthermore, the diagnostic diagram for rapeseed oil until 60 minutes test is "high energy – arc discharge".

Component of DGA	Time of Discharge (minute)					
	15	30	60			
$C_{2}H_{2}/C_{2}H_{4}$	1.50	1.67	1.67			
$C_{2}H_{2}/C_{2}H_{6}$	3.00	3.33	3.33			
$C_{2}H_{4}/C_{2}H_{6}$	2.00	2.00	2.00			

**Table 3.5** Composition ratio gas generation rate in mineral oil.

**Table 3.6** Composition ratio gas generation rate in rapeseed oil.

Common of DCA	Time of Discharge (minute)					
Component of DGA	15	30	60			
$C_{2}H_{2}/C_{2}H_{4}$	6.00	5.00	3.12			
$C_{2}H_{2}/C_{2}H_{6}$	2.00	5.00	13.25			
$C_{2}H_{4}/C_{2}H_{6}$	0.33	1.00	4.25			



Figure 3.14 ETRA criterion data for mineral oil and rapeseed oil under corona discharge. (a) Diagnosis A, (b) Diagnosis B

#### **3.3.5** Diagnostic Results of Duval Triangle

The diagnostic method according to the IEC, composition gas ratio in Chapter 2 was calculated to be used in the analysis of the Duval triangle from Equations (13), (14) and (15). Table 3.7 and Table 3.8 show the composition gas ratio of rapeseed oil and mineral oil, respectively. Figure 3.15 shows a plot of calculated values results in the Duval triangle. Rapeseed oil is classified as D1 (low energy discharge) in all conditions while mineral oil is classified as D2 (high energy discharge) in all conditions.

**Table 3.7**Composition gas ratio in mineral oil.

Percentage of	Time of Discharge (minute)			
component of DGA	15	30	60	
% CH <sub>4</sub>	13	20	13	
$%C_{2}H_{4}$	13	13	21	
$%C_{2}H_{2}$	75	67	66	

Percentage of	Time of Discharge (minute)			
component of DGA	15	30	60	
% CH <sub>4</sub>	17	20	18	
$%C_2H_4$	33	30	31	
$%C_2H_2$	50	50	51	

**Table 3.8**Composition gas ratio in rapeseed oil.



Figure 3.15 The diagnostic results of Duval triangle.

#### 3.4 CONCLUDING REMARKS

The component of gases dissolved in natural rapeseed oil and mineral oil by the impulse arc discharge and corona discharge was analyzed using the stripping extraction method and the gas chromatograph. A sort of discharge was also evaluated on the bases of the diagnostic criterion in the ETRA and IEC (using the Duval triangle).

The results obtained for the impulse arc discharge are summarized as follows.

(A) The energy consumed by the arc discharge was smaller in an positive impulse voltage than in the negative one and its difference was large in rapeseed oil than in mineral oil. A great amount of C<sub>2</sub>H<sub>2</sub> gas was dissolved in both the discharge treated rapeseed oil and mineral oil. Rapeseed oil also dissolved much more CO gas than mineral oil. A dissolved amount of gasses depended on the polarity of applied voltage and a sort of oils. For the positive discharge, rapeseed oil had detectable gasses such as  $CH_4$ ,  $C_2H_4$  and  $C_3H_8$  higher than the negative discharge. However, in mineral oil, the amounts of these gasses for the negative discharge exceeded slightly those for the positive discharge. The amount of  $CH_4+C_2H_4+C_3H_8$  in both rapeseed oil and mineral oil increased by the increase of the number of discharge  $N_A$ , while H<sub>2</sub> gas had a tendency to decrease by the increase of the  $N_A$ . In both rapeseed oil and mineral oil, the impulse arc discharge was diagnosed as "Discharge" or "High-energy discharge" in the diagnostic charts based on the ETRA criterion. On the other hand, the diagnostic chart based on the IEC (Duval triangle) criterion indicated "Low-energy discharge".

On the other hand, the experiments on dissolved gas-in-oil analysis (DGA) in oils under AC corona discharge are summarized as follow:

(B) Discharge power consumed by the corona discharge in rapeseed oil was almost the same as that in mineral oil; 0.30 ~ 0.33 W. Then, the combustible gases dissolved in rapeseed oil were a large amount than in mineral oil, that is, the amount of gases (C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, CH<sub>4</sub> and CO) dissolved in rapeseed oil was larger than that in mineral oil for the 60 minutes test of the discharge. Furthermore, the amount of dissolved gases in rapeseed oil increased steeply for the discharge time exceed 50 minutes, especially it was remarkable in the amount of C<sub>2</sub>H<sub>2</sub> gas. In the diagnostic charts based on the ETRA criterion, the AC corona discharge in both rapeseed oil and mineral oil was diagnosed as "Discharge" which belongs to "Medium energy discharge" for the 30 minutes test of the discharge, but the AC corona discharge in rapeseed oil for the 60 minutes test of the discharge was diagnosed as "High energy - arc discharge". The diagnostic chart based on the IEC (Duval triangle) criterion revealed that the AC corona discharge in rapeseed oil was classified as "Low energy discharge", while in mineral oil, it was classified as "High energy discharge", for all discharge tests up to 60 minutes.

Because rapeseed oil has many advantages on the environmental compatibility and electrical insulation performance, it is expected for insulation design of an environmentally fitted power transformer as a substitute of mineral oil. The results obtained in this research indicate that a feature of faults inside transformers used rapeseed oil can be specified by the same diagnostic criterion as mineral oil.

## **CHAPTER IV**

# CREEPING STREAMER PROGRESSED IN DIELECTRIC BARRIER WITH NARROW GAP IN PFAE OIL [25, 114]

#### 4.1 OBJECTIVE OF RESEARCHING

The compound insulation systems which are composed of insulating oil and oil-impregnated cellulose products (pressboard (PB), kraft paper (KP), wood etc.) have widely been employed to insure the inside electrical insulation of high-voltage apparatuses such as oil-filled power and distribution transformers, power capacitors etc. The use of a conventional petroleum-based mineral oil (the so-called transformer oil) as insulating oil, however, has a considerable risk because of the recent some environmental problems. Thus, the environmentally inoffensive oils such as natural ester oils (vegetable-based oils) and synthetic oil have been required for a substitute of mineral oil. PFAE (palm fatty acid ester) oil (i.e. one of vegetable-based oils) which is expected as the new oil candidate for power transformers fitted in the environment is used in this research. It is known recently that the PFAE oil has many advantages on environmental compatibility and electrical insulation performance [72]. On the other hand, the oil/solid (cellulose products) interface in composite insulation systems will be considered as an electrical weak point which the creeping streamer is easier progress by stressing lightning surge indeed. Study on the creeping discharge is most important for a designer who expert in the oil insulated power apparatuses, because the progression of the creeping streamer leads to flashover accident. Generally, the flashover in composite insulation system pursues complicated course of streamer progression including the oil/solid interface, narrow gap between pressboards, pressboard punch-through breakdown, etc. Many studies on the creeping discharges have been performed for a single interface of oil/solid at normal pressure and temperature [19-20, 27, 52, 115].

The aim of this research is to obtain further understanding on the properties of creeping discharge progressed in the narrow gap between two solid dielectrics under

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lightning impulse voltages [26]. The experimental set up and procedure are presented in this section. The behaviors of creeping streamer in palm fatty acid ester (PFAE) oil have been investigated in comparison with those in mineral oil (transformer oil: JIS-C2320). The growth of positive and negative streamers depends on the gap space between two solid dielectrics. By decreasing the gap spacing, the flashover voltage is largely increased, while the mean velocity of positive streamer is significantly decreased under the both polarities of impulse voltage. In this research, it is shown that the behaviors of creeping discharge in both oils elegantly reveal the distinctive phenomena.

#### 4.2 EXPERIMENTAL SETUP AND PROCEDURE

#### 4.2.1 Electrode System

Figure 4.1 depicts the schematic of electrode system used in this research. A high density pressboard with three dimensions; 70 mm width, 170 mm lenght and 3 mm thickness was used as the solid dielectric. Pressboard was first dried for 24 hours at 60 °C and then impregnated with the sample oil under vacuum conditions to remove moisture and gasses from the fibrous structure as much as possible. The surface of this pressboard has small elliptical dimples (~0.29 mm width, ~0.82 mm length and ~0.013 mm depth in size), which is arrayed uniformly by the compression within the manufacturing process. A tungsten needle with a tip radius ~ 30 µm was installed against a grounded counter electrode (copper plate) in the one side of pressboard surface. The needle electrode was inclined by an angle of  $\sim 30^{\circ}$  and was used as a high voltage electrode. The distance between the needle tip and the counter electrode was 50 mm. The grounded copper rod with the dimension of 2 mm in diameter and 50 mm in length was also installed as a back side electrode (BSE) on the other side of pressboard as shown in Figure 4.1, and it was connected to a counter electrode. On the other hand, the region (50-70 mm<sup>2</sup> in area) between the needle tip and the counter electrode on the pressboard was covered by a transparent acrylic resin plate (with the optical transmission of 93 %) of 10 mm thick in order to arrange a narrow gap space  $\Delta D$  which can initiate the creeping streamer. The aspect of the discharge was observed through the



Figure 4.1 Schematic of electrode

transparent acrylic resin. The  $\Delta D$  between the pressboard and the acrylic plate was adjusted in the range of 0.1 to 2.0 mm by the spacer with a regular thickness.

#### 4.2.2 Measuring System of Creeping Discharges

Figure 4.2 shows the schematic of the measuring system. The electrode system was immersed completely into the sample oil, and it was kept in the test vessel filled gaseous nitrogen (GN<sub>2</sub>) with 99.999 % purity using a vacuum pump and GN<sub>2</sub> cylinder. The gap between solid dielectrics in the electrode system was filled completely at the sample oil by a vacuum pump. The counter electrode was grounded through a current detection system (Tektronix Inc.) consisting of the probe (TCP312) and amplifier (TCP300) to measure the discharge current. The current sensitivity measurement was 100 MHz in frequency and less than 3.5 ns in rising time. The lightning impulse voltages  $V_{p}$ , up to  $\pm 140$  kV<sub>peak</sub> were applied to the needle electrode. The voltage waveforms with  $\pm 1.2/50 \,\mu s$  and  $\pm 1.2/1000 \,\mu s$  were selected to compare the effect of the wave tail of applied voltages on the growth of creeping streamers. The discharge shapes were photographed using a still camera equipped with a night viewer (C5100, Hamamatsu Photonics Inc.). In these photographic data, the streamer length  $L_m$  was defined as the length of streamer progressed toward the counter electrode from the needle tip. The  $L_m$  was plotted as the average of twenty trials under identical applied voltage. Each impulse voltage was applied at ~ 15 minute intervals. The flashover



C.P.: Current probe, I.I.: Image intensifire, I.C.C.: Image converter camera

Figure 4.2 Schematic of measuring system.

voltage was also recoded. The progression steps of the streamer were then recorded by using a high-speed image converter camera (ICC: IMACON 468, Nac Inc.) to determine a temporal variation of the streamer velocity.

All experiments were performed at room temperature in the atmospheric pressure.

#### 4.3 EXPERIMENTAL RESULTS AND DISCUSSION

#### 4.3.1 Discharge Shapes and Associated Currents

Figure 4.3 shows the typical example of the discharge shapes and associated currents for 0.1 mm and 2.0 mm in the space  $\Delta D$ . In the case of  $\Delta D$ =0.1 mm (Figure 4.3a and Figure 4.3b), many intermittent current pulses were observed in the wave tail of applied voltages. It is regarded that these pulses are corresponding to the individual branches of the streamer. The sustaining time of current pulse for the negative streamer is longer than that for the positive streamer. The length of negative streamers is always longer than that of positive streamers under identical applied voltage. The positive streamer progresses in the spreadable extension without a clear directivity, but the negative streamer along the linear site of BSE.



(c)  $\Delta D=2.0 \text{ mm}, V_p=\pm 50 \text{ kV}$ 

Figure 4.3 Typical example of discharge shapes and associated currents.

On the other hand, the streamers in both polarities of  $\Delta D=2.0$  mm (Figure 4.3c) grow longer than these of  $\Delta D=0.1$  mm (Figure 4.3a) and a flashover at  $\Delta D=2.0$  mm occurs when the applied voltage exceeds  $V_p=\pm60$  kV<sub>peak</sub>. The streamers in both polarities show a tendency to progress along the linear site of BSE. The length of negative streamers is shorter than the positive streamers under identical applied voltage,

which is a reverse relation to that in  $\Delta D$ =0.1 mm. This dependence of the streamer polarity on the length at  $\Delta D$ =2.0 mm is identical with the streamer progression at an oil/solid single interface without the gap between solid dielectrics. The associated current pulses generate intermittently for the front time of applied voltages.

#### 4.3.2 Streamer Lengths and Flashover Voltage

Figure 4.4(a) and (b) shows the relationships between the streamer length  $L_m$  and the applied voltage  $V_p$  in PFAE oil for the voltage waveforms with  $\pm 1.2/50$  µs and  $\pm 1.2/1000$  µs, respectively. In these figures,  $L_m=50$  mm means the flashover between the needle tip and the counter electrode.

These properties display the dependence of  $\Delta D$  on the streamer length and flashover voltage. While, Figure 4.5(a) and (b) shows the relationships between  $L_m$  and  $V_p$  in mineral oil, which are compared with Figure 4.4(a) and (b).

The results in Figure 4.4 and Figure 4.5 represent the following facts:

- (1) In both PFAE oil and mineral oil, the impulse voltage with a long wave tail of  $\pm 1.2/1000 \ \mu$ s. It may aid the growth of the streamers in both polarities as compared with a short wave tail:  $\pm 1.2/50 \ \mu$ s, furthermore, the flashover voltage becomes low for the applied voltage with a long wave tail under identical  $\Delta D$  whatever the streamer polarity.
- (2) In the range of  $\Delta D$ =0.1-1.0 mm, the length of negative streamers in both PFAE oil and mineral oil is always longer than the positive streamers under identical applied voltage, it indicates that the negative flashover voltage is lower than the positive one under identical  $\Delta D$ .
- (3) In  $\Delta D$ =2.0 mm, the length of negative streamers in both PFAE oil and mineral oil becomes shorter than the positive streamers under identical applied voltage, so that the negative flashover voltage is higher than the positive one under identical  $\Delta D$ .
- (4) The streamer growth and flashover voltage in PFAE oil have roughly the same level as those in mineral oil.



(b)  $\pm 1.2/1000 \ \mu s$  impulse voltage

**Figure 4.4** Relationships between  $L_m$  and  $V_p$  in PFAE oil.

It is seemed that the effect of polarity on the streamer length in the range of  $\Delta D$ =0.1-1.0 mm is due to the presence of a narrow gap with two solid interfaces, especially, the growth of the positive streamer is given to be restrained because of a restriction of the oil domain in the narrow gap. The positive streamer will be able to secure a vital power to progress when the  $\Delta D$  is extended up to 2.0 mm. A flashover voltage  $V_f$  also depends on the growth of streamers in relation to the  $\Delta D$ .





(b)  $\pm 1.2/1000 \ \mu s$  impulse voltage

Figure 4.5 Relationships between  $L_m$  and  $V_p$  in mineral oil.

Figure 4.6 shows the relationships between the flashover voltage  $V_f$  and the space  $\Delta D$ . For two applied voltages with  $\pm 1.2/50 \ \mu s$  and  $\pm 1.2/1000 \ \mu s$ , the positive flashover voltages for the space  $\Delta D$  less than ~ 1.2 mm are higher than the negative flashover voltages, but when the  $\Delta D$  exceeds ~ 1.2 mm, this polarity effect on the V<sub>f</sub> is reversed. This will be consistent with the dependence of  $\Delta D$  on the streamer growth.



**Figure 4.6** Relationships between  $V_f$  and  $\Delta D$  in PFAE oil.

#### 4.3.3 Temporal Variation of Streamer Growth

Figure 4.7 shows the typical stepping images of the streamer growth in PFAE oil taken at an ICC for three types of  $\Delta D$ . The relationships between the streamer length  $L_m$ and the time t obtained from these photographic data are shown in Figure 4.8. In this figure, it is clear that the slope of curves in both polarities represents the temporal variation of the streamer velocity. As soon as the streamer starts, it is accelerated abruptly for the time to crest of the voltage  $(\pm 1.2 \,\mu s)$  and after reaching to the maximum velocity  $u_{max}$ , it reduces velocity steeply. After that the velocity attenuates gradually while repeating the acceleration and deceleration. On the other hand, the mean velocity  $u_m$  can roughly be estimated from the ratio of the maximum length of streamer  $L_p$  to the sustaining time of current pulse  $t_p$ ;  $u_m = L_p/t_p$ . The  $u_m$  and  $u_{max}$  of the streamer in both polarities are shown in Table 4.1 for three types of  $\Delta D$ . The mean of velocity  $u_m$  of the positive streamer is affected by the  $\Delta D$  than the negative streamer. In the positive streamer, the  $u_m$  was slowed down with the decreasing of  $\Delta D$ , while for the negative streamer, the  $u_m$  is almost independent of  $\Delta D$ . The maximum velocity  $u_{max}$  of the positive streamer depends on the  $V_p$  rather than  $\Delta D$ , where, the  $u_{max}$  becomes fast with the increase of  $V_p$ , but the  $u_{max}$  of the negative streamer has roughly the same value in spite of the  $\Delta D$  and  $V_p$ .





(a)  $\Delta D=0.1$  mm,  $V_p=\pm70$  kV,  $\pm 1.2/1000$  µs







Figure 4.7 Typical stepping images of streamer growth.



**Figure 4.8** Relationships between  $L_m$  and t. (PFAE oil,  $\pm 1.2/1000 \ \mu s$  impulse voltage)

Spacing Voltage	Positive strea	mer velocity	Negative streamer velocity		
$\Delta D \text{ [mm]}$	$V_p$ [kV] mean value m $u_m$ [km/s] u		maximum u <sub>max</sub> [km/s]	mean value <i>u<sub>m</sub></i> [km/s]	maximum u <sub>max</sub> [km/s]
0.1	±70	~ 2.5	~ 6.4	~ 1.2	~ 2.5
0.5	$\pm 70$	~ 3.6	~ 6.9	~ 1.0	~ 2.4
2.0	$\pm 50$	~ 4.7	~ 3.7	~ 1.1	~ 2.0

**Table 4.1**  $u_m$  and  $u_{max}$  of the streamer in both polarities.

#### 4.4 CONCLUDING REMARKS

On the behaviors of creeping discharges progressed in a narrow gap between two solid dielectric plates in PFAE oil, the effect of the gap spacing  $\Delta D$  in the range of 0.1 to 2.0 mm was investigated using the impulse voltages up to  $V_p = \pm 140 \text{ kV}_{\text{peak}}$  with  $\pm 1.2/50$  $\mu$ s and  $\pm 1.2/1000 \mu$ s. The streamer length and flashover voltage have a distinctive polarity effect on the  $\Delta D$ . The length of negative streamers in  $\Delta D$ = 0.1-1.0 mm is always longer than the positive streamers under identical applied voltage. While in  $\Delta D=2.0$  mm, the length of negative streamers is shorter than the positive streamers which has the same dependence as the streamer progressed in an oil/solid single interface without the gap. Consequently, the flashover voltage becomes low in the negative voltage for the  $\Delta D$  less than ~ 1.2 mm, but in the positive voltage when the  $\Delta D$ exceeds ~1.2 mm. The polarity effect on the streamer length in  $\Delta D$ =0.1-1.0 mm is due to the presence of a narrow gap, especially, the growth of the positive streamer is restrained by a restriction of the oil domain in the narrow gap. The mean velocity  $u_m$  of the positive streamer also slows down with decreasing  $\Delta D$ , but the  $u_m$  of the negative streamer is almost independent of  $\Delta D$ . Additionally, the streamer growth and flashover voltage in PFAE oil are roughly the same level as those in mineral oil.

### **CHAPTER V**

# AC CREEPING DISCHARGE ON VEGETABLE-BASED OIL / PRESSBOARD INTERFACE [53, 116]

#### 5.1 OBJECTIVE OF RESEARCHING

The electrical insulation is essentially one of the most important parts in high-voltage apparatuses such as power and distribution transformers. In the mineral oil/cellulose compound systems which have widely been employed as the electrical insulation technique, recently the environmentally inoffensive vegetable-based oils have newly been considered for a substitute of mineral oil [67, 72, 112], and the electrical insulation characteristics (partial discharge, creeping discharge, electrical breakdown, etc.) in these new insulating oils have been investigated in comparison with mineral oil for the last ten years [4, 13, 27, 54, 117-118]. Vegetable-based oils such as PFAE (palm fatty acid ester) oil and rapeseed oil are expected for insulation design of an environmentally fitted power transformer because of many advantages on the environmental compatibility and electrical insulation. However, these oils have a high moisture saturation limit (~ 2500 ppm at 20 °C), since it is prone to take up water in chemically bonded form or in dissolved form. This leads to the increase of dissipation factor and the reduction in volume resistivity or dielectric strength.

On the other hand, as mentioned above, an oil/solid interface of compound insulation systems in high-voltage apparatuses will be of concern as an electrical weak point due to a creeping discharge has easier progress under electric stress, because of the difference in permittivity between adjacent materials. The irreversible tree-like damage (tracking) is left on the solid surface as a result of these creeping discharges, and it results in a permanent electrically conductive path that deteriorates the insulation system. These events are regarded as one of the failure modes for the insulation system in power transformers [30, 49]. To guarantee a level of electrical insulation under high electrical stresses, the understanding of creeping discharge phenomena is most

important for a designer who is expert in oil insulated power apparatus.

The aim of this research is to make clearly the behavior of AC creeping discharges in vegetable-based insulating oils (palm fatty acid ester (PFAE) oil and natural rapeseed oil) and commercial mineral oil. The discharge shape, streamer extension, streamer velocity, tracking at the oil/pressboard interface, discharge current and dissipated energy have been examined as a function of the time and voltage under variable AC 60 Hz voltages up to 45 kV<sub>rms</sub> (root-mean-square values). The experimental preparation, setup and procedure are presented in this section. The gas components dissolved in oils by the creeping discharge are also examined by the DGA. In this research, it is presented that there are distinctive events due to the occurrence of creeping discharges, and these events have been discussed on the basis of the experimental results.

#### 5.2 PREPARATION OF EXPERIMENTS

# 5.2.1 Main Devices Used in Experiment ; Measurements of AC creeping discharge

The test on AC Creeping (or surface) discharge is one of the subjects which have been performed to examine the electrical insulation performance of dielectric fluids (mainly insulating oils), and the test data are extremely important for an insulating design of the power apparatus. In order to acquire the trustworthy experimental result, the sample oils should be free from both inside and outside moisture. Generally, the low moisture level inside the sample oil is realized by means of the vacuum process, and nitrogen gas (GN<sub>2</sub>) with 99.999 % purity is enclosed into the experimental container to protect the sample oil from outside moisture and oxygen.

In this research, a stainless steel container equipped a vacuum pump was designed and manufactured for the experimental observation of AC creeping discharge. The oil/ pressboard (PB) compound system with the needle electrode and back side electrode (BSE) was installed into a transparent acrylic test cell filled by the sample oil and its test cell was put into the stainless steel container. After the moisture and oxygen inside the container were removed by the vacuum pump, the container was filled by GN<sub>2</sub>



Figure 5.1 Schematic of stainless steel container and transparent acrylic test cell.



**Figure 5.2** Photograph of the container and acrylic test cell with oil/pressboard (PB) compound system.

(99.999 % purity). Figure 5.1 shows the schematic of stainless steel container and transparent acrylic test cell, and Figure 5.2 the photograph of the container and acrylic test cell with oil/ pressboard (PB) compound system used in the experiments.

The schematic of designed needle electrode also is shown in Figure 5.3. The design of the transparent acrylic test cell which can introduce 10.5 liters of the sample oil is shown in Figure 5.4. AC creeping discharges are generated in the sample oil inside this test cell and observed through the window of the stainless steel container.



Figure 5.3 Design of needle electrode.



Figure 5.4 Design of transparent acrylic test cell.

#### 5.2.2 Sample Oils and Moisture Control

PFAE (palm fatty acid ester) oil, natural rapeseed oil and commercial mineral oil (transformer oil: JIS-C2320) were used as sample insulating oils in this research. PFAE oil and rapeseed oil were provided from Lion Corporation and Kanden Engineering Corporation in Japan, respectively. The main properties of oil samples are shown in Table 2.4 (see Section 2.1 in Chapter II). PFAE oil and rapeseed oil are better than mineral oil for environmental safety, because of an excellent biodegradability and non-toxicity. The flash points of PFAE oil and rapeseed oil are higher than mineral oil, and mineral oil does not only slightly generate dioxins but also toxic products under fire condition, while there is no toxicity in the vegetable-based oils. The kinetic viscosity is lower in PFAE oil, but much higher in natural rapeseed oil as compared with mineral oil. PFAE oil and rapeseed oil also improve the insulation coordination in permittivity between adjacent materials, because of their high relative permittivity. The electrical breakdown voltage is higher than mineral oil at low moisture level conditions, which is advantageous for electrical insulation in the oil/pressboard compound insulating system.

The moisture level in the sample oils was controlled so as to fit in the actual moisture content of the insulating oil in the power transformers by means of both a vacuum pump and bubbling of  $GN_2$  (99.999 % purity).

Figure 5.5 illustrates the moisture control process, and Figure 5.6 shows the photograph doing the moisture control. Furthermore, sample oils were dried for 24



Figure 5.5 Schematic of moisture control process.



Figure 5.6 Photograph doing the moisture control.

hours at 60 °C under vacuum conditions. As a result, moisture levels in PFAE oil, rapeseed oil and mineral oil measured by a Karl Fisher titration were 77.4 ppm, 65.1 ppm and 36.8 ppm, respectively.

#### 5.2.3 Pressboard Treatment and Electrode Arrangement

A high density pressboard with three dimensions; 70 mm width, 170 mm length and 3 mm thickness was used as the solid dielectric. The surface of this pressboard has small elliptical dimples (~ 0.29 mm width, ~ 0.82 mm length and ~ 0.013 mm depth in size), which is arrayed uniformly by the compression within the manufacturing process. Pressboard was first dried for 24 hours at 60 °C and then impregnated with the sample oil under vacuum conditions to remove moisture and gasses from the fibrous structure as much as possible. Figure 5.7 shows the schematic of the pressboard drying process, and Figure 5.8 the schematic for preparation of the sample oil-impregnated pressboard. Subsequently, the oil-impregnated pressboard was immersed completely into the same oil (10.5 liters) in a transparent acrylic test cell.



Figure 5.7 Pressboard drying process.



Figure 5.8 Preparation of oil-impregnated pressboard.

Tungsten needle with a tip radius ~ 30  $\mu$ m was installed as the point electrode in the one side of pressboard surface as shown in Figure 5.9. The needle was placed at an angle of ~ 30° to the pressboard surface and was used as a high voltage electrode. The acute angle of the needle electrode will lead the streamer to one direction rather than radial direction. In this research, the counter electrode was not installed on the pressboard to avoid the surface flashover between the needle tip and the counter electrode. The other side of pressboard has a grounded copper rod (2 mm diameter and 100 mm length) which has been adhered tightly by an epoxy resin as a back side electrode (BSE). The needle tip on the pressboard surface was positioned just above the one end of the BSE. This is simulating the oil/pressboard compound insulation system in an actual oil-filled power apparatus for the experimental research on creeping discharges.



Figure 5.9 Schematic of electrode system.

#### 5.3 EXPERIMENTAL SETUP AND PROCEDURE

Figure 5.10 shows the schematic of the experimental setup employed to observe the behavior of creeping discharges. An acrylic test cell equipped the electrode system in Figure 5.9 was put into the stainless steel vessel filled  $GN_2$  (99.999 % purity) by using a vacuum pump and GN<sub>2</sub> high-pressure tank to avoid the oxidation of oil and invasion of moisture. Variable AC 60 Hz voltages V<sub>rms</sub> in the range of 0 to 45 kV (root-mean-square) were applied to the needle electrode by a testing transformer with maximal output voltage of 100 kV (AG-100K50, Nissin Pulse Electronics Inc.). The voltage waveform was monitored by an oscilloscope through the high-voltage probe with 1/5000 output (EP-100K, Nissin Pulse Electronics Inc.). In a certain value of applied voltage, after the inception of the partial discharge at needle tip, the creeping streamer progressed gradually over the pressboard surface to parallel and normal directions to the BSE. The discharge shapes were photographed using a still camera equipped with a night viewer (C5100, Hamamatsu Photonics Inc.). These photographic data were taken as a function of the time and voltage to obtain the features of streamer growth. In this research, the parallel and normal streamer extensions to the BSE were estimated by measuring the maximal length  $L_m$  from needle tip to streamer head and maximal width  $W_m$  of the streamer over both sides of the BSE, respectively. The  $L_m$  and  $W_m$  were plotted as the average of five trials under identical applied voltage. The distinct feature on the pressboard surface occurred in the middle of the streamer growth was observed photographically. The pressboard puncture event and the marks on pressboard surface appeared after the creeping discharge development were also observed.

Electrical current and dissipated energy based on the creeping discharge were examined by using an electro-optic coupling circuit and a Sawyer-Tower circuit, respectively, as shown in Figure 5.10. The discharge currents were detected by two light emitting diodes (LED1 and LED2 in a reversed parallel connection), which were connected to the needle electrode (high voltage side). The light emitted from the LED was transmitted to a photodiode through a light guide. Thus the current flowing through



Figure 5.10 Schematic of experimental setup.

the needle electrode at a half cycle in positive and negative polarities of the alternating voltage might be detected by LED1 and LED2, respectively [42-44]. The light of discharge was also observed by the naked eye with the aid of a night viewer. The energy dissipated by the creeping discharge was measured by the  $\Delta V$ -Q Lissajous diagram monitored from the low voltage  $\Delta V$  divided by a high voltage probe and the electric charge Q of a capacitor  $C_0$  (0.1 µF) connected between the BSE and the ground. The dissipated energy  $J_i$  can be calculated as [68]

 $J_i = V_s Q f = m S f C_0 \qquad \text{joule/second} \qquad (17)$ 

where  $V_s$  denotes the discharge sustaining voltage, f the frequency of applied voltage (60 Hz), m the voltage dividing ratio (5000) and S the area of the Lissajous diagram.

On the other hand, the gas components dissolved in oils by the creeping discharge were examined by means of gas chromatography (GC). The schematic of the gas analysis system used in this research and the measurement conditions of dissolved gases are shown in Figure 3.3 and Table 3.1 (see Section 3.1.3).

All experiments were performed at room temperature in the atmospheric pressure.

#### 5.4 EXPERIMENTAL RESULTS AND DISCUSSION

#### 5.4.1 Discharge Current, Creeping Discharge Feature and Dissipated Energy

Figure 5.11 shows typical examples of the current waveform taken as a function of the time  $t_m$  under a fixed voltage. First, the partial discharge (PD) was initiated at the needle tip when the applied voltage exceeded the critical value withstand of the bulk oil. The discharge current at this time was observed in the form of many pulses as shown in Figure 5.11(a). The local breakdown at the needle tip was attributed to an ionization process in the oil at the high electric field level of more than approximately 2 MV/cm. The number of pulses was numerous in the negative half cycle as compared with positive one of the applied voltage. This suggests that the impact ionization process due to the electrons emitted from the needle tip takes precedence over the field ionization process. Such the PD pattern was changed to the shape of creeping streamer which slowly grew to parallel and normal directions to the BSE after a short duration (roughly 1 to 2 minutes) of the voltage application. The amplitude and number of current pulses during the streamer growth became smaller than those observed for PD as shown in Figure 5.11(b). The streamer growth will be associated with the ionization at a low energy in gaseous layer or low-density region. The streamer growth will be associated with the ionization at a low energy in gaseous layer or low density region of oil on or near the oil/pressboard interface rather than the bulk oil. The current pulses, however, increased greatly when the pressboard was approaching to the punch-though breakdown event, as shown in Figure 5.11(c). These features on the current waveform were observed similarly for all oil samples used here.

Typical photographic profiles of creeping streamers taken as a function of the time  $t_m$  imposing the voltage for PFAE oil, rapeseed oil and mineral oil are shown in Figure 5.12, respectively. The streamer growth will be associated with the ionization at a low

energy in gaseous layer or low density region of oil on or near the oil/pressboard interface rather than the bulk oil. The current pulses, however, increased greatly when the pressboard was approaching to the punch-though breakdown event, as shown in Figure 5.11(c). These features on the current waveform were observed similarly for all oil samples used here.



(c)  $t_m=25$  min: Approach to pressboard puncture

**Figure 5.11** Typical examples of discharge current waveform.  $(V_{rms}=35 \text{ kV}, \text{ oil sample}: \text{Rapeseed oil})$ 



**Figure 5.12** Typical photographic profiles of creeping streamers as a function of the time. ( $V_{rms}$ =35 kV)

Typical photographic profiles of creeping streamers taken as a function of the time  $t_m$  imposing the voltage for PFAE oil, rapeseed oil and mineral oil are shown in Figure 5.12, respectively. The following features were found from these observations on growth of creeping streamers. The streamers were characterized by many formations of a fine branching and flashing spot. The flashing spots were clearly located in the head of streamer branches which indicated an ionization zone. It could be observed through a night viewer that the flash in rapeseed oil and mineral oil emitted a light brighter than that in PFAE oil. The streamers were easy to develop in the parallel direction rather than normal direction to the BSE. The streamer velocity in rapeseed oil and mineral oil was faster than that in PFAE oil, and the length  $L_m$  and width  $W_m$  of the streamer channel were longer than those in PFAE oil at the same discharge duration. The streamers in rapeseed oil and mineral oil had a lot of fine branches with many small flashing spots, while the streamer in PFAE oil was of a few thick branches.

The energy  $J_i$  dissipated by the occurrence of creeping discharges was measured as a function of the time tm under a fixed voltage and the typical result is shown in Figure 5.13. The energy  $J_i$  increased with the time, which revealed that the creeping discharge spread gradually its area over the pressboard surface. The  $J_i$  in rapeseed oil and mineral oil was larger than that in PFAE oil. This reflects that the creeping streamer in both rapeseed oil and mineral oil has an extension larger than that in PFAE oil at the same



Figure 5.13 Energy dissipated by creeping discharges.

discharge duration, as shown in photographic profiles of Figure 5.12. The  $J_i$  -values dissipated during the creeping discharge will be able to produce a high temperature which is enough to decompose the cellulose or oil in a local area nearest to the streamer channels.

#### 5.4.2 Gas Components Dissolved in Oils by Creeping Discharge

The gas components dissolved in oil samples (typically rapeseed oil and mineral oil) after the creeping discharge treatment were examined by using the gas analysis system in Figure 3.3 and Table 3.1 in chapter III. Seven gas components; hydrogen (H<sub>2</sub>), methane (CH<sub>4</sub>), ethane (C<sub>2</sub>H<sub>6</sub>), ethylene (C<sub>2</sub>H<sub>4</sub>), acetylene (C<sub>2</sub>H<sub>2</sub>), carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) were chosen as a target of gas analysis in this research. The ppm value of gases generated in oils is shown in Table 5.1 which indicates the following features. The relatively small amount of CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub> and C<sub>2</sub>H<sub>4</sub> was detected in both rapeseed oil and mineral oil at the discharge duration of 20 minutes, and the amount of H<sub>2</sub> and C<sub>2</sub>H<sub>2</sub> was much larger than ppm values of above gases. CO and CO<sub>2</sub> were also detected in both oils. The amount of CO in rapeseed oil was more than that in mineral oil and CO<sub>2</sub> was included much more than CO. The amount of nitrogen (N<sub>2</sub>) gas given for reference was normally much greater than other gases, because of gaseous nitrogen filled in the test vessel with the oil sample.

Dissolved gases		$H_2$	$CH_4$	$C_2H_6$	$C_2H_4$	$C_2H_2$	CO	$CO_2$	$N_2$
Limit of quantitation		5	1	1	1	0.2	2	2	50
Rapeseed	$t_m = 5 \min$	6	1	1	1	5	8	117	63601
oil	$t_m=20 \min$	12	3	3	3	15	17	263	61536
Mineral oil	$t_m = 5 \min$	5	2	1	2	8.4	3	178	65823
	$t_m=20 \min$	22	11	3	4	29	4	212	67690
* $t_m$ : Discharge duration unit: (ppm)									

**Table 5.1**Gases generated in oils.

It is well known that when the dielectric oils such as mineral oil are subjected to high thermal and electrical stresses, various gases generate due to the decomposition of the oil. As mentioned in Chapter II - Section 2.6, the C-H molecular bonds are produced or decomposed at lower temperatures or energy, and higher temperatures or energy are necessary to produce or decompose the C-C single bonds, C=C double bonds and C=C triple bonds. The creation of gases depends on the temperature, and the fault gases are generated in the order of  $H_2 \rightarrow CH_4 \rightarrow C_2H_6 \rightarrow C_2H_4 \rightarrow C_2H_2$  with an increase of temperature. H<sub>2</sub> gas appears at the temperature in the range of 100 to 150 °C. CH<sub>4</sub> and  $C_2H_6$  gases with the C-H and C-C single bonds respectively can be formed at the temperature in the range of 250 to 350 °C.  $C_2H_4$  gas with C=C double bond can also be formed at higher temperature in the range of 200 to 500 °C. The formation of C<sub>2</sub>H<sub>2</sub> with C=C triple bond starts at the temperature exceeding 500 °C (usually 500 to 700 °C) [40, 41]. Meanwhile, if an oil-impregnated cellulose is involved in the oil, CO and CO<sub>2</sub> gases can be generated due to cellulosic thermal decomposition at lower temperature than that for oil decomposition (above a threshold temperature of approximately 150 °C). CO<sub>2</sub> gas increases much more rapidly than CO with an increase of temperature.

Conventionally, the DGA fault diagnostic can be estimated by the Duval triangle method which has been standardized by the International Electro-technical Commission (IEC) [19, 20]. The Duval triangle plots of the DGA data obtained in the present research belong to "low energy discharges" in both rapeseed oil and mineral oil. However, the discharge energy leads to the rise of temperature similar to or exceed 500 °C at the local region on or nearby the creeping streamer channels, because of the fact
that  $C_2H_2$  gas is detected by the occurrence of creeping discharges as shown in Table 5.1.

### 5.4.3 Streamer Extensions and Pressboard Puncture Event

The mean length  $L_m$  and width  $W_m$  of streamer channels in PFAE oil, rapeseed oil and mineral oil were plotted as a function of the time and voltage from the photographic data for five trials, respectively. Figure 5.14 shows the  $L_m$  and  $W_m$  as a function of the



**Figure 5.14**  $L_m$  and  $W_m$  as a function of time  $t_m$  for different voltages.

time  $t_m$  for different voltages. The streamer growth exhibits roughly a linear dependence on the time  $t_m$ , which the slope of curves represents the mean velocity of streamers. The mean streamer velocities  $u_L$  and  $u_W$  in parallel and normal directions to the BSE are shown in Table 5.2. The  $u_L$  was much faster than  $u_W$  under identical applied voltage. This indicates clearly the effect of the BSE on the streamer growth. Although rapeseed oil and mineral oil were significantly different in a kinetic viscosity, the  $u_L$ -value was faster than that in PFAE oil with a low viscosity. This indicates that the streamer growth is independence from the kinetic viscosity of oils for ac creeping discharges. Figure 5.15 shows the  $L_m$  and  $W_m$  as a function of the voltage  $V_{rms}$  for three oil samples. The  $V_{rms}$  was elevated gradually every 3-minute intervals. The partial discharge incepted similarly at 20 kV in both PFAE oil and mineral oil, while this initiated at 25 kV in

**Table 5.2** Mean streamer velocities  $u_L$  and  $u_W$  in parallel and normal directions to BSE.

	Applied voltage $V_{rms}$ (kV)						
Oil samples	30		35		40		
	$u_L$	$u_{\scriptscriptstyle W}$	$u_L$	$u_{\scriptscriptstyle W}$	$u_L$	$u_{\scriptscriptstyle W}$	
	(mm/min)		(mm/min)		(mm/min)		
PFAE oil	0.8	0.19	0.8	0.3	0.8	0.5	
Rapeseed oil	1.7	0.2	3.2	0.4	5.6	0.9	
Mineral oil	1.7	0.4	2.5	0.6	3.3	1.2	



**Figure 5.15**  $L_m$  and  $W_m$  as a function of applied voltage  $V_m$ .

rapeseed oil. The electric fields at the needle tip for these inception voltages are estimated as ~2.2 MV/cm in both PFAE oil and mineral oil and ~2.8 MV/cm in rapeseed oil. The  $L_m$  and  $W_m$  increased clearly with the increase of  $V_{rms}$ , and  $L_m$  in rapeseed oil was much longer than that in PFAE oil and mineral oil at  $V_{rms}$ >35 kV.

A sudden puncture breakdown of the pressboard occurred in the middle of the streamer progression. The time  $t_B$  from the voltage application to the puncture is shown in Figure 5.14 which is marked by an arrow as a minimal time for five trials. The  $t_B$  decreased when the  $V_{rms}$  was increased, although it had a large standard deviation. The pressboard puncture occurred at the position separated approximately 2 to 5 mm from the needle tip. This may be caused by the relaxation of the electric field near the needle tip due to the accumulation of space charges [62, 90].

# 5.4.4 Formation of Surface Tracking

When the creeping discharge developed on the pressboard surface as shown in Figure 5.16(a), a white mark which resembled to a discharge shape appeared on the pressboard surface as shown in Figure 5.16(b). The white mark grew-simultaneously with the streamer growth from initial discharge at the needle tip. Then many tiny bubbles floating in the oil were observed at the surrounding area of streamer branches. The formation of this white mark is thought to be associated with a gas generated into the pressboard or bulk oil during the streamer progression. As predicted from the dissipated energy and DGA data (Figure 5.13 and Table 5.1), a higher temperature more than  $\sim 500$  °C can locally be produced on or nearby the streamer channels. The oil or moisture inside the pressboard surface. Consequently, the created gases are put out from the fibrous structure of cellulose because of the gas expansion. Maxwell's stress also will promote this effect. In this case, Maxwell's stress is forced toward to the pressboard surface including a lot of gases will become smaller than that in the oil area.

Then, the oil is pulled into the pressboard and it acts so as to put out gases from the cellulosic structure. The gases generated by heating, however, will be captured in the small pores at the pressboard surface due to the surface tension of the oil and cellulose fibers. This results in a drying process on the pressboard surface and appears as the white mark which is covered by a thin gaseous layer or low density region of oil. The formative process of the white mark is illustrated in Figure 5.17. Overheating nearby the streamer channels will also decompose the oil molecules and produce the fault gases which may channels will also decompose the oil molecules and produce the fault gases which may partially be captured in the pores of the pressboard surface. When the gases captured in the pores were expanded to the size exceeding the surface tension, tiny gas bubbles will be visualized in the bulk oil as observed in this research. As a result, the head of streamer branches can be developed by an active ionization due to the presence of the white mark, even if the lower energy than that in bulk oil. When a test vessel was



(a) Example of creeping discharge.  $(V_m=35 \text{ kV}, t_m=15 \text{ min})$ 



(b) White mark on pressboard surface after creeping discharge.



(c) Tracking pattern with dark marks on pressboard surface.

**Figure 5.16** Typical patterns of creeping discharge, white mark and tracking on pressboard surface. (sample oil: rapeseed oil)



Figure 5.17 Formative process of white mark.

evacuated by a vacuum pump after the creeping discharge development, the white mark disappeared from the pressboard surface at a short time. This is evidence of the presence of a drying area containing micro-bubbles at the oil/pressboard interface.

The creeping discharge left the irreversible tracking pattern with dark marks on the pressboard surface as shown in Figure 5.16(c). A considerable high temperature is produced at a local area nearest to the streamer channels by the discharge energy as mentioned above. The heat energy is transmitted directly to the dried area of the pressboard surface through the oil with high thermal conductivity (typically 0.13 to 0.18 W/m·K). Then the cellulose fibers are carbonized by overheating, because the temperature for carbonization of cellulose is more than approximately 400 °C. Consequently, the tree-like tracking damage is formed on the pressboard surface. Once tracking was formed on the pressboard surface, the streamer progressed through the discharge with similar pattern as Figure 5.16(a) occurred at a tracking area on the pressboard. Subsequently, the streamer started to grow gradually at its head again. Figure 5.18 shows the relation between  $L_m$  and  $t_m$  for the pressboard with and without the tracking under a fixed applied voltage. It is evident that the development of ac



**Figure 5.18** Typical relation between  $L_m$  and  $t_m$  for pressboard with and without tracking damage.

creeping discharges is promoted greatly by the tracking damages on the pressboard surface, because of an electrically conductive property of carbonic paths.

### 5.4 CONCLUDING REMARKS

The creeping discharges in PFAE oil, rapeseed oil and mineral oil were investigated using the oil/pressboard system with the needle electrode and grounded rod type BSE under AC 60 Hz voltages up to 45 kV in rms.

The creeping streamer developed slowly on the pressboard surface in the shape with many branches under a fixed voltage. Then, the phenomena with the flashing spots indicating an ionization zone at the head of streamer branches were also observed in this experiment. The flashes in rapeseed oil and mineral oil emitted a light more luminous than in PFAE oil. The streamer expanded to the parallel direction rather than normal direction to the BSE. The streamer velocity in rapeseed oil and mineral oil was faster than that in PFAE oil, and the streamers grew longer than PFAE oil under the same discharge duration. The streamers in rapeseed oil and mineral oil had a lot of fine branches with many small flashing spots, while the streamer in PFAE oil was of a few thick branches. A puncture breakdown of the pressboard occurred suddenly in the middle of the streamer growth. The time up to the puncture event decreased when the imposed voltage was increased.

Furthermore, the creation of  $C_2H_2$  gas obtained from the DGA suggested that the temperature at a local region on or nearby the creeping streamer channels was risen up to more than at least 500 °C by the discharge energy. A white mark on the pressboard surface resembled to a discharge shape appeared synchronously with streamer growth. This was attributed to a drying process due to the electrical and thermal effects. The creeping discharge left a dark tree-like tracking damage indicating a carbonized conductive path on the pressboard surface. Such the tracking damage promoted greatly the development of AC creeping discharges.

# **CHAPTER VI**

# CREEPING DISCHARGE IN AGED RAPESEED AND MINERAL OILS [120]

### 6.1 OBJECTIVE OF RESEARCHING

The insulating oil bears an important function in both the electrical insulation (in combination with cellulose products) and the decrease of thermal losses (in cooling effect) inside the power apparatus such as oil-filled transformers. Mineral oil has been employed in the majority of the power apparatuses over more than a century, but nowadays, vegetable-based oils which are chemically classified as natural esters have been considered as substitutes of mineral oil, because of the demand for environmentally friendly insulating oils in distribution and power transformers [71, 73]. Thus the application to power transformers of these new oils will bring great profits compared to conventional mineral oil. In these transformers, oil/pressboard compound systems have widely been used to insure the internal electrical insulation. The surface of oil-impregnated pressboards, however, is concerned as electrical weak point which the creeping discharges can easily progress, because of the difference in permittivity between adjacent materials [15, 27, 53]. Furthermore, the aging of the oil and cellulose materials results in one of the major inducements to the transformer failures, because the insulator aging will significantly affect to the creeping discharge characteristics which lead to the degradation of insulation systems [13, 49, 50, 121, 123]. Although abundant experimental results on the creeping discharge have been reported by many researchers, the aging effects on the behaviors of creeping discharges have not been understood well, especially for use of vegetable-based oils.

The aim of this research is to make clearly the behavior of creeping discharges in rapeseed oil and mineral oil with a heat-accelerated aging and to obtain further understanding of creeping discharges on pressboard. In this work, the aging effect of oils on the discharge shape, streamer extension, streamer velocity, discharge current waveforms, discharge energy, pressboard surface tracking and pressboard puncture is examined experimentally under the applied AC high voltages. The creeping discharge events have been compared with those in new oils without the aging.

# 6.2 PREPARATION OF EXPERIMENTS

#### 6.2.1 Experimental Setup and Procedure

Experiments were carried out in laboratory to investigate the creeping discharge along the oil/pressboard interface under variable AC 60 Hz voltages up to 40 kV (effective values). Experimental procedure for AC creeping discharge in the aged oils is similar to that for AC creeping discharge in the normal oils and the schematic diagram of experiment also is the same as Figure 5.10 in Chapter V.

The schematic of the electrode arrangement is shown in Figure 5.9 in Chapter V. A high density pressboard with 70 mm width, 170 mm length and 3 mm thickness was used as the solid dielectric. After the pressboard was first dried for 24 hours at 60 °C, it was impregnated with the sample oil under vacuum conditions to remove moisture and gasses from the fibrous structure. Subsequently, the electrode system was immersed completely into 0.7 liters of the same oil in a transparent acrylic test vessel. A tungsten needle with a tip radius ~ 50  $\mu$ m was installed on one side of the pressboard surface as a high voltage electrode. The needle was placed at an angle of ~30° to the pressboard surface. In this work, the counter electrode was not installed on the pressboard to avoid the surface flashover between the needle tip and the counter electrode. The other side of pressboard has a grounded copper rod (2 mm diameter and 100 mm length) which was adhered tightly by an epoxy resin as a back side electrode (BSE). The needle tip on the pressboard surface was positioned just above one end of the BSE.

An acrylic test vessel with the electrode system and sample oil was put into the stainless steel vessel filled with gaseous nitrogen (GN<sub>2</sub>: 99.999 % purity) to avoid the oxidation of oil and invasion of moisture. Variable AC 60 Hz voltages  $V_{\rm rms}$  up to 40 kV in root-mean-square were applied to the needle electrode by a test transformer (AG-100K50, with maximal output voltage of 100 kV, Nissin Pulse Electronics Inc.). The applied voltage was monitored by an oscilloscope through the high-voltage probe

with 1/5000 output (EP-100K, Nissin Pulse Electronics Inc.). The shapes of discharge propagating on the oil/pressboard interface were photographed by a still camera equipped with a night viewer (C5100, Hamamatsu Photonics Inc.). These photographic data were taken as a function of the time and voltage to obtain the features of streamer growth. The streamer extensions were estimated by measuring the maximal length  $L_m$ from needle tip to streamer head and maximal width  $W_m$  of the streamer over both sides of the BSE, respectively. The  $L_m$  and  $W_m$  were plotted as the average of three trials under identical applied voltage. The marks on pressboard surface appeared after the discharge development and the pressboard puncture were also observed.

Electrical current and dissipated energy based on the creeping discharge were examined by using an electro-optic coupling circuit and a Sawyer-Tower circuit, respectively (see Figure 5.10 in Chapter V). The discharge currents were detected by two light emitting diodes in a reversed parallel connection (LED1 and LED2 in Figure 4) which were connected to the needle electrode. The light emitted from the LED was transmitted to a photodiode through a light guide. Thus, the current flowing through the needle electrode at a half cycle in positive and negative polarities of the alternating voltage can be detected by LED1 and LED2, respectively. The energy dissipated by the creeping discharge was measured by the  $\Delta V$ -Q Lissajous diagram monitored from the low voltage  $\Delta V$  divided by a high voltage probe and the electric charge Q of a capacitor  $C_0$  (0.1 µF) connected between the BSE and the ground. The dissipated energy  $J_i$  can be calculated as  $J_i = V_s Qf = mSfC_0$  joule/second, where  $V_s$  denotes the discharge sustaining voltage, f the frequency of applied voltage (60 Hz), m the voltage dividing ratio (5000) and S the area of the Lissajous diagram.

All experiments were performed at room temperature in the atmospheric pressure.

# 6.2.2 Preparation of Heat-Accelerated Aging Oils

The heat-accelerated aging samples of rapeseed oil and mineral oil were provided by Kanden Engineering Corporation in Japan. The aged oil samples were produced through some processes at the laboratory level. The heat-accelerated aging process of oils is presented schematically in Figure 6.1. The process is explained as follows:

(1) First, the three glass bottles with 5 litters of sample oil were prepared and the copper coils with 1 mm in diameter and total length of 80 m were immersed in each bottle as a metallic catalyst.

(2) After the three bottles were connected in series by an insulating pipe, the dry air was supplied into the upper space of the sample oil through the pipe. Then, the output of pipe was inserted in the bottom of a test tube with water (300 mm deep) and the air pressure was adjusted at approximately 2.9 kPa by a pressure adjustment to obtain uniform pressure of each sample oil.

(3) The underpart of three glass bottles was put into a thermostatic oil-bath tank at more than 125 °C, so that three sample oils were kept at 125 °C by convection.

(4) After three weeks, the copper coils were exchanged for the new coils because the coil surface was covered by the sludge.

(5) The acid value in the sample oil was measured successively, and when it exceeded 0.3 mgKOH/g, the heating process was turned off.



A: Dry air, B: 5 L glass bottle, C: Sample oil (with convection),
D: Copper coils (as catalysis), E: Pressure adjustment (~ 2.9 kPa),
F: Thermostatic oil-bath tank



(6) After the sample oil was filtered through the membrane filter with a pore size of 0.8  $\mu$ m to remove the sludge, it was adjusted to the acid value at 0.3 mgKOH/g by mixing the new oil.

(7) Finally, the aged sample oil was put into the oil vessel and it was sealed hermetically after bubbling nitrogen gas at the flow rate in ~ 5 L/min for ~ 20 minutes.

Rapeseed oil and mineral oil without the aging were of transparency, but they changed to a dark brown colour for rapeseed oil and a soft brown colour for mineral oil by a heat-accelerated aging as shown in Figure 6.2. The sample oils were dried for 24 hours at 60 °C under vacuum conditions to remove the moisture.



Figure 6.2 Sample oils with and without aging.

Physical and electrical properties	Rapeseed (new oil)	Rapeseed (aged oil)	Mineral (new oil)	Mineral (aged oil)
Density (20°C) g/cm <sup>3</sup>	0.92	0.94	0.88	0.88
Kinetic viscosity (40°C) mm <sup>2</sup> /s	36.0	76.2	8.13	8.64
Breakdown voltage (Moisture level: 10 ppm or less) kV/2.5mm	74	63	70-75	62
Relative permittivity (80°C)	2.86	4.39	2.20	2.17
Dissipation factor: tan δ (80°C)	8.3×10 <sup>-2</sup>	3.5×10 <sup>-1</sup>	1.0×10 <sup>-3</sup>	5.0×10 <sup>-3</sup>
Volume resistivity (80°C) $\Omega \cdot cm$	4.4×10 <sup>12</sup>	3.1×10 <sup>10</sup>	7.6×10 <sup>15</sup>	4.4×10 <sup>12</sup>

**Table 6.1**Main properties of sample oils with and without aging.

The main physical and electrical properties were also measured for sample oils with and without the aging. It will be recognized that the kinetic viscosity of rapeseed oil becomes much higher by the aging compared to that of mineral oil [55] and the electrical properties of the oil are degraded in aged both oils than those of new oils as shown in Table 6.1.

# 6.3 EXPERIMENTAL RESULTS AND DISCUSSION

### 6.3.1 Creeping Discharge Shape, Streamer Extension and Pressboard Puncture

Typical photographic profiles of creeping streamers taken as a function of the time  $t_m$  imposing the voltage for rapeseed oil and mineral oil with and without the aging are shown in Figure 6.3, respectively.







**Figure 6.3** Typical photographic profiles of creeping streamer as function of time for oils with and without aging. ( $V_{rms}$ =35 kV)



**Figure 6.4**  $L_m$  and  $W_m$  as function of time  $t_m$  for oils with and without aging. ( $V_{rms}=35 \text{ kV}$ )

In oils with and without the aging, the creeping streamer propagated gradually to parallel and normal directions to the BSE along the pressboard surface after the partial discharge inception in the needle tip at a certain value of applied voltage. The streamer shape was characterized by a lot of fine branches and flashing spots. The flashing spots were located in the head of streamer branches which indicates an ionization zone. The streamers were easy to develop in the parallel direction rather than normal direction to the BSE.

The mean length  $L_m$  and width  $W_m$  of the streamer in oils with and without the aging are shown typically in Figure 6.4 as a function of the time  $t_m$  for different voltages, which are plotted from the photographic data of the discharge. The time  $t_B$  from the voltage application to the pressboard puncture also is shown in the figure. The streamer extension has roughly a linear dependence on the time  $t_m$ . The streamer growth in aged oils, however, is facilitated than that in new oils under identical time imposing the voltage. The slope of these curves also represents the mean velocity of streamers. The mean streamer velocities  $u_L$  and  $u_W$  in parallel and normal directions to the BSE are shown in Table 6.2. The  $u_L$  is much faster than  $u_W$  under identical applied voltage. Furthermore, the  $u_L$  in aged oils is faster than that in new oils. This indicates the aging effect of oil on the streamer growth. As shown in Table 6.1, although the kinetic viscosity of rapeseed oil, especially the aged oil, is much larger than that of mineral oil, a significant different between both oils cannot be found on the  $u_L$ -value under identical applied voltage. This means that the velocity of the streamer growth is independent from the kinetic viscosity of oils for AC creeping discharges. A high kinetic viscosity in rapeseed oil, however, will be disadvantageous to the cooling effect for applying to power apparatus. A puncture breakdown of the pressboard occurs suddenly at near the needle tip in the middle of the streamer propagation. Although the  $t_B$ -value in Figure 6.4 has a large standard deviation, the mean values of  $t_B$  are shown roughly in Table 6.3. The  $t_B$  decreases with increasing the  $V_{rms}$  and the  $t_B$ -value in aged oils is lower than that in new oils under a fixed applied voltage.

Insulating oil		Applied voltage V <sub>rms</sub> (kV)						
		30		35		40		
		<i>u</i> <sub>L</sub> (mm	<i>u</i> w n/min)	<i>u</i> <sub>L</sub> (mm	<i>u</i> <sub>w</sub> n/min)	$u_L$ (mm.	<i>u</i> w /min)	
Rapeseed oil	New oil	1.56	0.24	2.80	0.25	5.00	0.80	
	Aged oil	2.00	0.27	3.86	1.00	6.50	1.33	
Mineral oil	New oil	1.54	0.29	2.50	0.40	3.30	0.67	
	Aged oil	1.71	0.25	3.00	0.50	6.00	2.00	

**Table 6.2** Mean streamer velocities  $u_L$  and  $u_W$  in parallel and normal directions to BSE for oils with and without aging.

**Table 6.3** Mean values of time  $t_B$  from voltage application to pressboard puncture.

Voltage (kV)	Time <i>t</i> <sup>B</sup> until pressboard puncture (min)						
	New mineral oil	Aged mineral oil	New rapeseed oil	Aged rapeseed oil			
30	~69	~66	~72	~53			
35	~28	~27	~30	~24			
40	~22	~19	~17	~16			

### 6.3.2 Discharge Current and Dissipated Energy

A notable difference on the creeping discharge characteristics in the oils with and without the aging appears in the current waveforms. The current accompanying the creeping discharge is observed in the form of many pulses. The local breakdown (partial discharge: PD) in the bulk oil at the needle tip is attributed to an ionization process at the high electric field of more than approximately 2 MV/cm as mentioned in Chapter 5. The PD pattern changes to the shape of a creeping streamer after a short duration (1 to 2 minutes) of the voltage application and it extends slowly in parallel and normal directions to the BSE. The amplitude of current pulses during the streamer growth becomes much larger in aged oils than that in new oils under identical applied voltage as shown in Figure 6.5. This reveals that the ionization activity is promoted by the aging of oils.



**Figure 6.5** Typical examples of discharge current waveform for oils with and without aging. ( $V_{rms}$ =35 kV)

The heat-accelerated aging oil contains the component of copper used as a metallic catalyst, and the ionization phenomenon may be activated by the copper component in aged oils [123].

The energy  $J_i$  dissipated by the creeping discharges was measured for oils with and without the aging. Figure 6.6 shows the typical results of the  $J_i$  obtained from the  $\Delta V$ -QLissajous diagram as a function of the time  $t_m$  under a fixed voltage. The dissipated energy increases with the time by the gradual extension of the creeping discharge. The  $J_i$  in aged oils is larger than that in new oils under the same discharge duration, because of the large amplitude of current pulses in aged oils. These  $J_i$ -values will raise greatly the temperature of a local area nearest to the streamer channels, so that the cellulose or oil in a local area can be decomposed by the propagation of creeping discharges.



**Figure 6.6** Energy dissipated by creeping discharges in oils with and without aging. ( $V_{rms}$ =35 kV)

## 6.3.3 Pressboard Surface Tracking

In both oils with and without the aging, a white mark which is similar to a discharge shape appears on the pressboard surface along with the growth of creeping streamer. This white mark disappears from the pressboard surface at a short time when a test vessel is evacuated by a vacuum pump after the discharge propagation. It is thought that a white mark is formed by a drying process due to the electrical and thermal effects as mentioned in Chapter 5. The creeping discharge also leaves permanently a dark tree-like tracking damage as shown in Figure 6.7. This indicates a carbonized conductive path on the pressboard surface. On the other hand, by the propagation of creeping discharges, the fault gases such as hydrogen (H<sub>2</sub>), methane (CH<sub>4</sub>), ethane  $(C_2H_6)$ , ethylene  $(C_2H_4)$  and acetylene  $(C_2H_2)$  are detected in the oil as mentioned in Chapter 5. The generation of these gases is mainly caused by a high thermal stress in the oil. Generally, it is known that the fault gases are generated in the order of  $H_2 \rightarrow CH_4 \rightarrow C_2H_6 \rightarrow C_2H_4 \rightarrow C_2H_2$  with an increase of temperature, especially,  $C_2H_2$  gas generates at the temperature exceeding 500 °C (usually 500 to 700 °C). In this work, the fact that C<sub>2</sub>H<sub>2</sub> gas is detected by the occurrence of creeping discharges suggests that the local region on or nearby the creeping streamer channels can be raised up to



**Figure 6.7** Typical patterns of white mark and tracking on pressboard surface. (sample oil: rapeseed oil)

the temperature similar to or exceed 500 °C. This forms the tracking on the pressboard surface, because the temperature for the carbonization of cellulose is more than approximately 400 °C. The tracking damage promotes greatly the creeping discharges.

# 6.4 CONCLUDING REMARKS

Using rapeseed oil and mineral oil with and without the heat-accelerated aging, the aging effect of oils on the creeping discharge characteristics was investigated under the applied voltages up to ac 40 kV<sub>rms</sub> with 60 Hz. The main results are summarized as follows.

In oils with and without the aging, the creeping streamer propagated slowly in the parallel direction rather than normal direction to the BSE installed in the pressboard. The streamer growth in aged oils was facilitated than that in new oils under identical time imposing the voltage. The discharge current was observed in the form of many pulses. The amplitude of current pulses during the streamer growth was much larger in aged oils than that in new oils under identical applied voltage, which revealed that the ionization activity was promoted by the aging of oils. The energy dissipated by the creeping discharges in aged oils was larger than that in new oils under the same discharge duration due to the large amplitude of current pulses in the aged oils. The creation of  $C_2H_2$  gas based on the creeping discharges suggested that the temperature at

a local region nearest to the streamer channels was raised up to more than at least 500 °C by the discharge energy. This also means the formation of the tree-like tracking damage on the pressboard surface which promotes greatly the propagation of ac creeping discharges.

# **CHAPTER VII**

# **CONCLUSIONS AND FUTURE WORKS**

### 7.1 CONCLUSIONS (Research Summary)

Conventionally, a compound insulation system which is composed of insulating oil and oil-impregnated cellulose products (pressboard, kraft paper, wood etc.) has most often been employed in the inside electrical insulation of high-voltage apparatuses such as oil-filled power and distribution transformers for more than a century. The oil/solid interface in such the compound system, however, can be considered as an electrical weak point which the creeping streamer is easier progress under electric stress, because of the difference in permittivity between adjacent materials. Because the progression of the creeping streamer leads to flashover accident, the creeping discharge on solid insulation barriers is regarded as one of the failure modes for the insulation system in high-voltage apparatuses. Therefore, the understanding of creeping discharge phenomena is most important to guarantee a level of electrical insulation under high electrical stresses for a designer who is expert in oil insulated power apparatus.

Mineral oil has been used as the insulating oil, because of a high performance as electrical insulation and thermal coolant. However, recently, many programs to be solved such as poor biodegradation, low flash point, low relative permittivity, slight toxic, exhaustion of mineral resources in the near future, sulfide-induced corrosion of copper, atmospheric pollution due to burning and pollution of the ground water due to oil leakage have been pointed out for mineral oil from a viewpoint of the protection of the environment. Nowadays, the environmentally inoffensive vegetable-based oils have been expected as a substitute of mineral oil, and the comparison between vegetable-based oils and mineral oil on the properties of the partial discharge, creeping discharge and electrical breakdown phenomena have been reported by several researchers for the last ten years.

In this research, PFAE (palm fatty acid ester) oil and natural rapeseed oil were used to clarify the behavior of creeping discharges in the vegetable-based oils by using the variable impulse voltages up to  $\pm 140 \text{ kV}_{\text{peak}}$  with  $\pm 1.2/50 \text{ }\mu\text{s}$  and  $\pm 1.2/1000 \text{ }\mu\text{s}$  waveforms and the variable ac 60 Hz voltages up to 45 kV in root-mean-square values. The present paper describes the experimental research on the creeping discharges developing on the insulating oil/pressboard interface. The research on the following four subjects was carried out in the laboratory to understand the behavior of creeping discharge. The experimental results in the vegetable-based oils were always compared with the results in mineral oil.

- Research (A): The research on the component of gases dissolved by various discharges in natural rapeseed oil and mineral oil (the gas-in-oil analysis (DGA) test) and the diagnostic evaluation based on the DGA test, which was described in CHAPTER III.
- Research (B): The research on the creeping streamer progressed in the dielectric barrier with a narrow gap in PFAE oil, which was described in CHAPTER IV.
- Research (C): The research on the AC creeping discharge traveling the vegetable-based oil / pressboard interface, which was described in CHAPTER V.
- Research (D): The research on the creeping discharge in the aged rapeseed and mineral oils, which was described in CHAPTER VI.

The main results of these researches are summarized as follows:

# <Research (A)>

The gases dissolved in natural rapeseed oil and mineral oil by the impulse arc discharge and corona discharge were analyzed using the stripping extraction method and the gas chromatograph. A sort of failures due to the discharges was also diagnosed on the bases of the ETRA and IEC (Duval triangle) criterions.

The results obtained from the impulse arc discharge are described below.

(1) The energy  $W_{BD}$  consumed by the positive arc discharge is smaller than that

consumed by the negative one, and the difference of  $W_{BD}$  on the voltage polarity is large in rapeseed oil.

- (2) A great amount of C<sub>2</sub>H<sub>2</sub> gas is dissolved in both rapeseed oil and mineral oil due to the arc discharge. Rapeseed oil also dissolves much more CO gas than mineral oil.
- (3) A dissolved amount of gasses depends on the polarity of applied voltage and a sort of oils. In rapeseed oil, the positive discharge produces detectable gasses such as CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub> and C<sub>3</sub>H<sub>8</sub> higher than the negative discharge. In mineral oil, however, the amounts of these gasses for the negative discharge are slightly larger than those for the positive discharge.
- (4) In both rapeseed oil and mineral oil, the amount of  $CH_4+C_2H_4+C_3H_8$  increases with increasing the number of discharge  $N_A$ , but  $H_2$  gas has a tendency to decrease with the increase of the  $N_A$ .
- (5) In both rapeseed oil and mineral oil, the impulse arc discharge is diagnosed as "High-energy discharge" in the diagnostic charts based on the ETRA criterion. However, the diagnostic chart based on the IEC (Duval triangle) criterion indicates "Low-energy discharge".

The results obtained from the AC corona discharge are described below.

- A difference between rapeseed oil and mineral oil on the electric power consumed by the corona discharge is small (it is 0.30 ~ 0.33 W in both oils).
- (2) The amount of combustible gases ( $C_2H_2$ ,  $C_2H_4$ ,  $C_2H_6$ ,  $CH_4$  and CO) dissolved in rapeseed oil is larger than that in mineral oil for 60 minutes test of the discharge. The amount of dissolved gases in rapeseed oil also increases steeply for the discharge time exceed 50 minutes, especially it is remarkable in the amount of  $C_2H_2$  gas.
- (3) The 30 minutes test of the AC corona discharge in both rapeseed oil and mineral oil is diagnosed as "Discharge" which belongs to "Medium energy discharge" in the diagnostic charts based on the ETRA criterion. However, the diagnosis for the 60 minutes test in rapeseed oil of the discharge belongs to "High energy - arc discharge".
- (4) The diagnostic chart based on the IEC (Duval triangle) criterion reveals that the corona discharge in rapeseed oil belongs to "Low energy discharge", while in mineral oil, it belongs to "High energy discharge", for all discharge tests up to 60 minutes.

Rapeseed oil is expected as a substitute of mineral oil for insulation design of an environmentally fitted power apparatus such as transformer. The results obtained in this research indicate that a feature of faults inside transformers filled rapeseed oil can be specified by the same diagnostic criterion as mineral oil.

#### <Research (B)>

The behaviors of creeping discharges developing in a narrow gap (the gap spacing  $\Delta D$  in the range of 0.1 to 2.0 mm) between two solid dielectric plates in PFAE oil were investigated using the impulse voltages up to  $V_p = \pm 140 \text{ kV}_{\text{peak}}$  with  $\pm 1.2/50 \text{ }\mu\text{s}$  and  $\pm 1.2/1000 \text{ }\mu\text{s}$ . The streamer length and flashover voltage have a distinctive polarity effect on the  $\Delta D$ . The main results obtained from this research are described below.

- (1) The length of negative streamers in  $\Delta D$ = 0.1-1.0 mm is always longer than the positive streamers under identical applied voltage.
- (2) In  $\Delta D=2.0$  mm, the length of negative streamers is shorter than the positive streamers. This relation is of the same dependence as the streamer progressed in an oil/solid single interface without the gap.
- (3) The flashover voltage becomes low in the negative voltage for the  $\Delta D$  less than ~ 1.2 mm, but in the positive voltage when the  $\Delta D$  exceeds ~1.2 mm.
- (4) The polarity effect on the streamer length in  $\Delta D$ =0.1-1.0 mm is due to the presence of a narrow gap, especially, the growth of the positive streamer is restrained by a restriction of the oil domain in the narrow gap.
- (5) The mean velocity  $u_m$  of the positive streamer also slows down with decreasing  $\Delta D$ , but the  $u_m$  of the negative streamer is almost independent of  $\Delta D$ .
- (6) The streamer growth and flashover voltage in PFAE oil are roughly the same level as those in mineral oil.

### <Research (C)>

The creeping discharges in PFAE oil, rapeseed oil and mineral oil were

investigated using the oil/pressboard insulating system with the needle electrode and grounded rod type BSE under AC 60 Hz voltages up to 45 kV in rms. The main results obtained from this research are described below.

- (1) The creeping streamer progresses slowly on the pressboard surface in the shape with many branches under a fixed voltage.
- (2) When the streamer progresses on the pressboard surface, the phenomena with the flashing spots indicating an ionization zone are observed at the head of streamer branches. The flashing spots in rapeseed oil and mineral oil emit a light more luminous than in PFAE oil.
- (3) The streamer expands to the parallel direction rather than normal direction to the BSE.
- (4) The streamer velocity in rapeseed oil and mineral oil is faster than that in PFAE oil, and the streamers grow longer than PFAE oil under the same discharge duration.
- (5) The streamers in rapeseed oil and mineral oil have a lot of fine branches with many small flashing spots, while the streamer in PFAE oil is of a few thick branches.
- (6) A puncture breakdown of the pressboard occurs suddenly in the middle of the streamer growth. The time up to the puncture event decreases when the imposed voltage is increased.
- (7) The creation of C<sub>2</sub>H<sub>2</sub> gas obtained from the DGA suggests that the temperature at a local region on or nearby the creeping streamer channels is risen up to more than at least 500 °C by the discharge energy.
- (8) A white mark on the pressboard surface resembled to a discharge shape appears synchronously with streamer growth. This is attributed to a drying process due to the electrical and thermal effects.
- (9) The creeping discharge leaves a dark tree-like tracking damage indicating a carbonized conductive path on the pressboard surface. Such the tracking damage promotes greatly the development of AC creeping discharges.

### <Research (D)>

Using rapeseed oil and mineral oil with and without the heat-accelerated aging, the aging effect of oils on the creeping discharge characteristics was investigated under the applied voltages up to ac 40 kV<sub>rms</sub> with 60 Hz. The main results obtained from this research are described below.

- In oils with and without the aging, the creeping streamer propagated slowly in the parallel direction rather than normal direction to the BSE on the pressboard surface. The streamer growth in aged oils was facilitated than that in new oils under identical time imposing the voltage.
- (2) The discharge current was observed in the form of many pulses. The amplitude of current pulses during the streamer growth was much larger in aged oils than that in new oils under identical applied voltage, which revealed that the ionization activity was promoted by the aging of oils.
- (3) The energy dissipated by the creeping discharges in aged oils was larger than that in new oils under the same discharge duration due to the large amplitude of current pulses in the aged oils.
- (4) The creation of C<sub>2</sub>H<sub>2</sub> gas based on the creeping discharges suggested that the temperature at a local region nearest to the streamer channels was raised up to more than at least 500 °C by the discharge energy. This also means the formation of the tree-like tracking damage on the pressboard surface which promotes greatly the propagation of ac creeping discharges.

Through these researches, it will be concluded that the vegetable-based oils such as PFAE oil and rapeseed oil which have many advantages on the environmental compatibility are highly recommended as the new liquid insulation candidate for the oil-filled power apparatuses fitted in the environment, because the electrical insulation performance can compare with mineral oil. It may safely be said that the use of vegetable-based oils to the power apparatus will bring great profits from a viewpoint of the protection of the environment in the near future.

### 7.2 FUTURE WORKS

The creeping discharge phenomenon occurs on the surface of cellulose insulation materials which are immersed in the insulating oil, and it leads to the failures of the insulation system in the power apparatus due to the accidents such as flashover and puncture breakdown. A deep understanding on the creeping discharge is very important for the electrical insulation design of oil-filled power apparatuses, because of a complicated mechanism of the creeping discharge phenomenon. Although the environmentally inoffensive vegetable-based oils proposed in recent years have been expected as a substitute of mineral oil, the researchers still face some subjects as follows.

- (1) The moisture distribution in oils is non-uniform, and cellulose materials will store a lot more moisture than the oil. The moisture effect of cellulose materials on the behavior of creeping discharges should be investigated in detail.
- (2) Other aging by-products such as insoluble oil sludge and carbon particles can be absorbed into the cellulose material. The effect of aging by-products on the behavior of creeping discharges should be investigated in detail.
- (3) The thermal aging effect of cellulose materials is also an important investigation on the behavior of creeping discharges.
- (4) It has been observed that the creeping discharges on the cellulose material (pressboard) can progress for long distance under low stresses. The investigation on this mechanism is important for the electrical insulation design.
- (5) The investigation on the behavior of creeping discharges under DC voltage and various impulse voltages is interested to obtain further understanding of the creeping discharges.

The experimental works on these subjects will be carried out in the near future.

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