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The Lightning Impulse Properties and Breakdown Voltage of Natural Ester Fluids Near the Pour Point

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Abstract – Recently, researchers have become interested in natural ester fluids, as they are an environmentally friendly alternative to mineral oils. Natural ester fluids are a natural resource made from plants; they have higher biodegradability, flash, and fire points, and a greater permittivity compared to conventional mineral oils. However, natural ester fluids also have a higher pour point, viscosity, and water content. These characteristics can hamper circulation and impair the electrical properties of an oil-filled transformer. A large amount of data has been accumulated over the years in regards to mineral insulating oil involving dielectric breakdown voltage and lightning impulse tests. However, natural ester fluids have not had their electrical properties sufficiently characterized. In this paper, we present an investigation into the characteristics of the electrical discharge development in natural ester fluids and in an oil-filled transformer near the pour points. The experiment results show that the electrical properties decreased according to a decrease in the ambient temperature and freezing time. It was found that the pour point and water content of natural ester fluids have a significant effect on the electrical properties.

Keywords: Natural ester fluids, Lightning impulse test, Chopped and full wave, Pour point, Viscosity, water content

1. Introduction

The dielectric liquids (mineral, natural ester fluids, etc.) used in electrical power equipment cool and insulate the internal components [1]. Mineral oil based fluids are widely used in power and distribution transformers. It is estimated that about 30 to 40 billion liters of mineral oil are currently in use in transformers worldwide. Government and environmental regulatory agents are enacting increasingly strict environmental laws and regulations in order to minimize the problems associated with dielectric fluid spillage and are imposing stiff penalties for spills, whether or not they are accidental [2]. In addition, the increasing petroleum oil crisis that is currently leading to an inevitable uncertainty in petroleum sustainability has forced researchers worldwide to find suitable alternate sources [3]. Today, not only are the oil performance and value key criteria in material selection, but the overall environmental and total life cycle costs are becoming part of the analysis [4]. In this context, natural ester fluids have been studied as a substitute for mineral insulating oils. Natural ester fluids have advantages in their improved fire safety, owing to a higher flash point and are 95~100% biodegradable, non-toxic, environmentally friendly, and have a high permittivity when compared to mineral insulating oils. Unfortunately, natural ester fluids also have a high pour point and viscosity. These characteristics hamper the circulation of the generated heat found in transformers which results in poor heat radiation [5]. Because of this, pour point depressants can be added when low pour points are needed.

In this paper, we discuss the thermal-electrical properties of natural ester fluids near the pour points. In order to investigate the breakdown behavior of the pressboard barriers under lightning impulses, stress tests using a real oil-filled transformer were performed. In addition, the influence of temperature on the dielectric breakdown voltage was investigated for different water content ranges in the natural ester fluids. Based on the results, we investigated the relationship between the natural ester fluid-filled transformer insulation and the environmental effects caused by temperature.

2. The Experiments

2.1 The insulating oil characteristics

The insulating oils tested in the experiments were Biotran-35 natural ester fluid and a commercial mineral oil provided by the Korea 'D' Petroleum Corp. The physical and electrical properties of the natural ester fluid and mineral oil are shown in Table 2. The viscosity of the natural ester fluid is about four times higher than that found for the mineral oil. The high viscosity of the natural

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ester insulating fluids is thought to be a critical issue in the safe operation of power and distribution transformers in cold weather countries. The transfer of heat in these transformers is done through both thermal conductivity and convection. The convection parameter is represented by all of the properties which lead to the heat transfer by fluid displacement (viscosity, specific heat, and the thermal expansion coefficient), whereas the conduction is transferred directly within the fluid [6]. In Table 1, the thermal conductivity of both mineral and natural ester fluids at 70°C shows no big difference. A low pour point and low viscosity allows the insulating oils to penetrate the solid insulation to help convey heat from the core materials in order to reduce the operating temperature and increase component life under a wide range of operating conditions. The temperature of the transformer doesn't decrease during normal operation, even at sub-zero ambient temperatures, due to sufficient amount of heat coming from the core and winding losses. But in the case of real transformer operation, the internal temperature of the transformer remains at about 70°C. In this case, the viscosity difference between the oils is more than four times (See Table 2). Adverse effects on the performance of the pump (flow pressure, and efficiency) can be felt when pumping a high viscosity fluid. This is not necessarily a critical issue, but care has to be taken, especially when designing the cooling system for power transformers [6]. It is most important to select a pump considering the viscosity. The pour point data shown in Table 1 indicates that natural ester fluids have a higher pour point compared to mineral oil. These higher pour point parameters in natural ester fluids indicate that there is a high risk of operating problems in very cold weather conditions [7]. When the supply of electricity due to a natural disaster is interrupted, the high pour point in the natural ester fluids can lead to major problems caused by freezing. The solidification of insulation fluid in a transformer could result in the formation of voids during a cold start leading to partial discharges (PD). PD initiation will weaken the insulation and may eventually lead to an electrical breakdown [8].

Table 1. The Heat Conductivity of the Mineral and Natural Ester Fluids

Contents	Temperature	Heat Conductivity (W/mK)	Diffusivity (mm^2/s)	Heat capacity (J /(g*K)
Mineral oil	25 ℃	0.214	0.125	2.003
	70 ℃	0.262	0.140	2.187
Natural ester fluids	25 ℃	0.245	0.141	1.877
	70 ℃	0.256	0.139	1.997

Table 2. The Physical and Electrical Properties of the Natural Ester and Mineral Insulating Oils.

Characteristics		Natural Ester Fluids	Mineral Oil
Viscosity [cSt]	40 [℃]	35.12	7.800
	100 [℃]	8.010	2.240
Specific Gravity [15/4℃]		0.924	0.855
Total Acid Value [mg KOH/g]		0.08	0.01
Dielectric Strength [kV]		78.8	75.0
Flash point [℃]		312	140
Pour point [℃]		-21	-50
Water Content [ppm]		20.7	15.0

2.2 The dielectric breakdown voltage test

The dielectric breakdown voltage of an insulating liquid is an important measure of the liquid's ability to withstand electrical stress without failure [9]. The insulating oil breakdown voltage depends on the presence of contaminants, such as water, dirt, or other conductive particles in the insulating oil. The measurement, following the KS C IEC 60156 standard [10], of the breakdown voltage was carried out using a fully automatic oil breakdown test equipment set, namely the Phoenix LD 60 (60㎸-60㎐) with 12.5 mm diameter spherical electrodes with a gap distance of 2.5mm. The voltage was progressively increased at a rate of 2.0±0.2㎸/s, from zero up to the breakdown. The breakdown voltage of natural ester fluids is typically beyond 60kV. The breakdown test equipment was reset for gap spacing to be 2.0mm, since it normally can measure only up to 60kV. All of the pertinent tests were run under the same conditions.

2.3 The lightning impulse test

In an oil-filled transformer the insulation system is built up using several composite insulation structures consisting of oil-impregnated pressboard layers. In order to investigate the electrical discharge development characteristics in a real natural ester fluid-filled transformer, the experiment was run using a transformer filled with pure natural ester fluid at a temperature near the pour point. The experiment considered a winter season power outage situation. According to the pour point of natural ester fluids, the refrigeration chamber temperature was maintained at -21°C

Fig. 1. The solidify the status of the natural ester fluid

or less. The transformer was cooled for at least 5 days in the refrigeration chamber without any power applied to it, resulting in purely external cooling. A 10-stage "Marx circuit" method was used during the digital impulse voltage test (system by HV TECHNOLOGIES, Inc.). The standard form, defined in IEC 60076-4 [11], employs a rising voltage from zero to the peak value over 1.2㎲, which then falls to 50% of the peak value over 50㎲. This is referred to as a 1.2/50㎲ negative polarity wave. Normally ASTM D3300 [12] is used for oils of petroleum origin. However, ASTM D6871 [13], the specification for natural ester fluids, recommends this standard.

3. Results and Discussions

3.1 The natural ester fluids breakdown voltage

We investigated the electrical discharge development characteristics in the natural ester fluids near the pour point. The natural ester fluids had a higher pour point compared to the conventional mineral oil. The dielectric breakdown voltage varies according to the environmental conditions, humidity, and temperature. Dry clean oil exhibits an inherently high breakdown voltage. Fig. 2 shows the fluctuation in the natural ester fluid breakdown voltage according to the temperature and freezing time. As the freezing time increased, the breakdown voltage steadily decreased, and approached its maximum voltage before a sharp under cooling. According to the cooling temperature results, under a low temperature the breakdown voltage decreases on a large scale. There appears to be two reasons for this: water content and ambient temperature. The water content is used by the industry to monitor an insulating oil's dielectric quality and as an indicator of possible oil deterioration, which could adversely affect the insulating oils electrical properties, such as its dielectric breakdown [14]. Natural ester fluids can hold considerably more water than conventional mineral oils. The room temperature

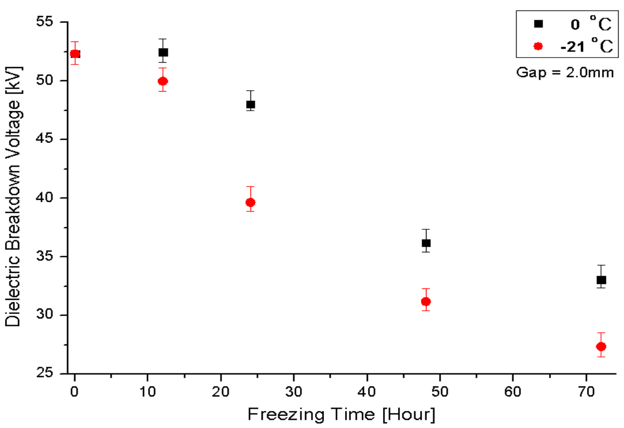

Fig. 2. The dielectric breakdown voltage of natural ester fluids at low temperatures

water saturation for the tested natural ester fluid is at about 1050㎎/㎏, whereas mineral oil is at about 60㎎/㎏. The dielectric strength of the insulating oil starts to fall when the water saturation reaches about 50% [15]. This higher moisture content results in some hydrolysis of the fluid, forming mild free fatty acids typical of ester-based fluids [16]. Mcshane et al [16] Fig. 11 shows the dielectric breakdown strength versus the water content for mineral oil and FR3 fluid. When the water content reached the 100㎎/㎏ the mineral oil dielectric breakdown voltage decreased rapidly. However, the natural ester fluids can accommodate a high water content, leading to a slow decrease with an increasing water content. Due to these aspects, the moisture content of natural ester fluids should be considered in relation to the water affinity. As shown in Table 2, the moisture content initial value of the natural ester fluid is higher than that found for the mineral oil. In addition, the natural ester fluid, due to high affinity for moisture, contains a lot of moisture in and of itself. Mcshane et al [16], Fig. 14 shows the dielectric breakdown strength versus the temperature for mineral oil and FR3 fluid. The results show that the breakdown voltage changes as the temperature changes. Depending on the amount of moisture and according to the ambient temperature, an increase in voids occurs in insulating oils. This can cause the dielectric breakdown voltage to be reduced. When the temperature approaches the pour point and the insulating oils freezes, this may indicate that the oil has deteriorated and may cause a lower dielectric breakdown voltage, which can damage the oil-filled transformer core and windings.

3.2 The lightning surge wave test results

As seen in Table 2, the natural ester fluid has a high pour point of -21℃ and a high viscosity. The mineral insulating oil pour point is -50℃. The natural ester fluid changes from a liquid to a solid when it reaches -21°C. As shown in Fig. 2, the natural ester fluids near its pour point has changes in its electrical characteristics. This low temperature can therefore be harmful to a natural ester fluid-filled transformer. The power transformer impulse wave test analyzes the conditions that exist when a transformer is subjected to an incoming high voltage surge due to lightning or other disturbances on its associated transmission line. The full wave application tests the ability of the insulation structure to withstand voltage surges; the chopped wave test simulates the stresses that occur in the collapse of a surge tail caused by the operation of a rod gap or a flashover to earth. Different times to chopping (Tc) in the chopped wave (as defined in IEC 60060-2 [17]) will result in different stresses (voltage and duration) in different parts of the winding(s) depending on the winding construction and arrangement employed. The time to chopping is therefore not regarded as a test parameter, provided that it is within the limits of 2㎲ and 6㎲as required by IEC 60076-4. Oscillograms or digital recording of the chopped waves, however, are only comparable for almost identical times to chopping [11]. In the case of lightning impulse voltage, the standard full wave shape of 1.2/50μs and the chopped wave shape of 1.2/2~6μs was used to test the pure natural ester fluids-filled transformer. The interpretation of the oscillograms or digital recordings is based on a comparison of the waveshapes of the voltages and current records between the reduced and rated test voltages or between successive records at a rated test voltage [11]. In Figs. 3~8, the characteristic curves show the variations of the maximum current to ground and their duration along the windings with the application of full impulses and chopped impulses at 50% and 100%. The chopped wave did not cause an electrical insulation problem. These results confirm that the chopped wave does not cause a problem at the solid state of the natural ester fluids. However, a problem occurred in regards to the full wave test. As shown in Fig. 6, the 1.2/50μs waveform and the current waveform in the full wave test at 50% were normal. As shown in Fig. 7, the normal full wave form (1.2/50μs) does not appear in the experiment sample (natural ester fluid-filled transformer). The problem of the current waveform was also observed in the second full wave test. On the basis of these results, after full wave tests on the windings of the internal oil-filled transformer problems can be expected. These experiments were conducted when approaching the pour point of the transformer oil with the power supply to the transformer disconnected. Long-term reliability of the transformer in a situation like this can therefore not be guaranteed.

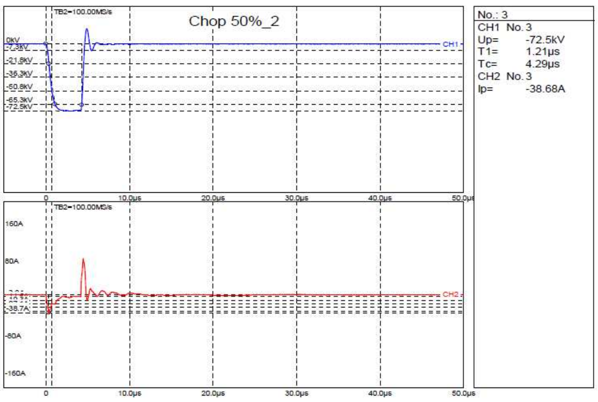

Fig. 3. The chopped wave test at 50%
(Front time T1=1.21 μs, Times to chopping = 4.29 μs)

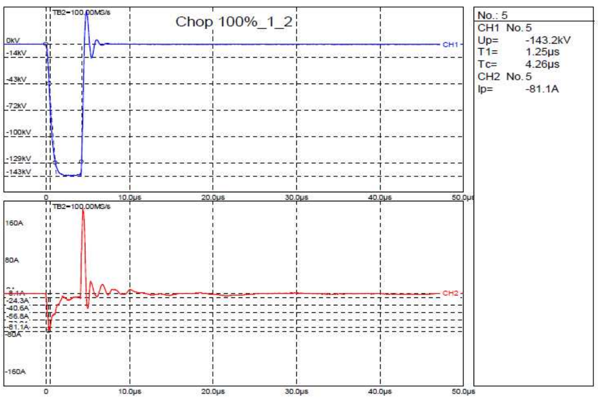

Fig. 4. The chopped wave test at 100% (1st Test)
(Front time T1=1.25 μs, Times to chopping = 4.26 μs)

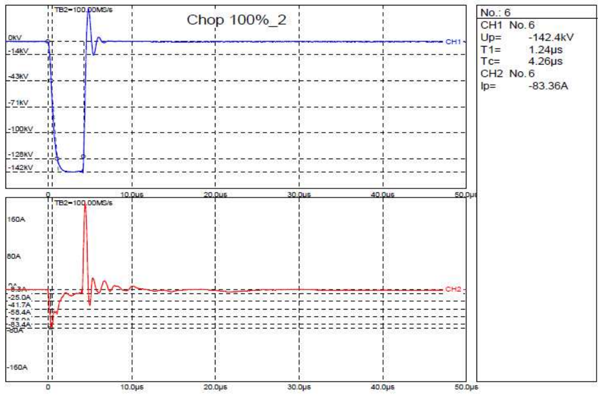

Fig. 5. The chopped wave test at 100% (2nd Test)
(Front time T1=1.24 μs, Times to chopping = 4.26 μs)

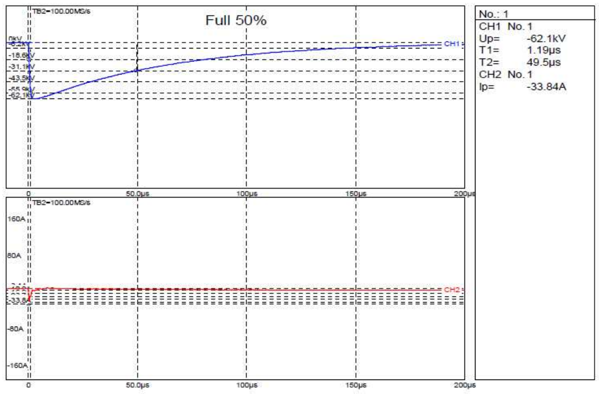

Fig. 6. The full wave test at 50%
(Front time T1=1.19 μs, Times to half-value = 49.5 μs)

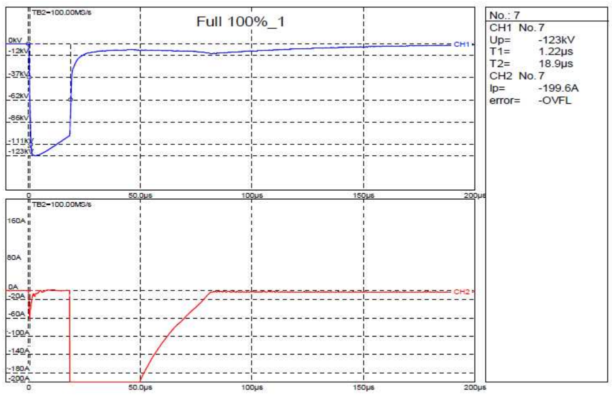

Fig. 7. The full wave test at 100% (1st Test)
(Front time T1=1.22 μs, Times to half-value = 18.9 μs)

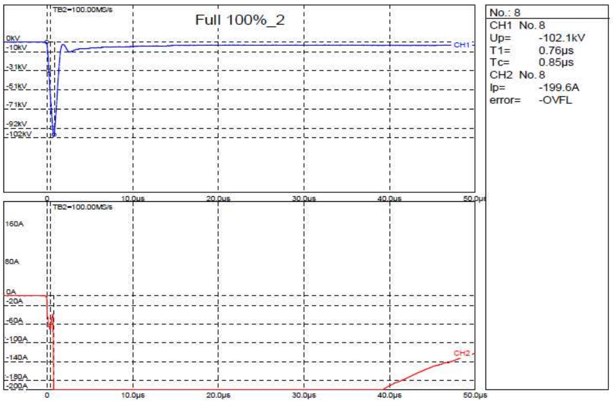

Fig. 8. The full wave test at 100% (2nd Test)

The transformer was disassembled after the lightning impulse tests for analysis. As shown in Fig. 9, the transformer windings were open after the test. The natural ester fluid-filled transformer windings broke down when the full lightning impulse test at 100% was run.

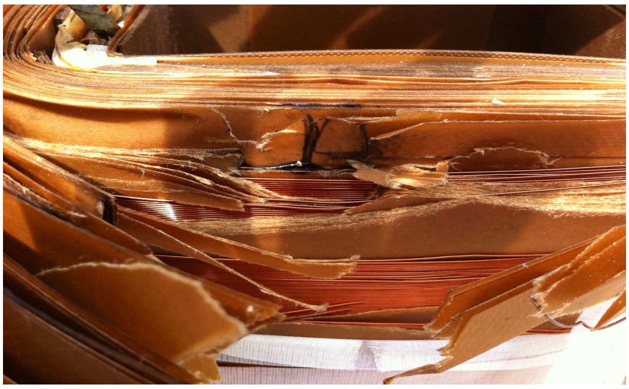

Fig. 9. The transformer winding breakdown after the full wave impulse voltage tests.

4. Conclusion

This study examined the dielectric breakdown voltage test and lightning impulse test for a natural ester fluid according to temperature. The experiment addressed the problems that may occur due to the high pour point. In an environment close to the transformer oil pour point, the insulating oil solidified. It was observed that there were changes in the breakdown voltage as the solid phenomena persisted. As a result, the dielectric breakdown voltage of natural ester fluids can gradually decrease. The breakdown voltage problem seen in natural ester fluids is related to their affinity for water. A pure natural ester fluid has a higher moisture content compared to conventional mineral oil and if exposed to an external environment will show a higher moisture content than mineral oil. A pure natural ester fluid-filled transformer that normally sits at room temperature failed when it was frozen (-21°C) after the lightning impulse test. It failed during the full wave portion of the lightning impulse. Therefore, the pour point and viscosity, water content data are important factors in natural ester fluids. This leads us to conclude that the design of heavy electrical machinery using natural ester fluids should be done carefully, taking into account the various temperature dependant factors.

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