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The effect of polarity on the lightning breakdown voltages of palm oil and coconut oil under a non-uniform field for transformers application

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ABSTRACT

This paper presents a study of the lightning breakdown voltages of Palm Oil (PO) and Coconut Oil (CO) under a non-uniform field with consideration on the polarity effect at various gap distances. All tests were carried based on a needle-sphere electrode configuration and various gap distances ranging from 2 to 25 mm under positive and negative voltage polarities. Three different testing techniques were used in this study including rising-voltage, up-and-down and multiple-voltage methods. The PO used in this study was Refined, Bleached and Deodorised Palm Oil (RBDPO) Olein. Three different samples of RBDPO and one sample of CO were tested. The Weibull distribution was used as a statistical approach to determine the withstand voltages of all samples at 1% and 50% probabilities for each type of oil. Under positive voltage polarity, it was found that the 50% breakdown voltages of RBDPO and CO were comparable with Mineral Oil (MO) whereby the highest percentage of difference among all gap distances was less than 15%. RBDPO and CO have lower 50% breakdown voltages than MO under a negative lightning impulse for which the highest percentage of difference can be up to 40%.

1. Introduction

Currently, Palm Oil (PO) and Coconut Oil (CO) are among the types of vegetable oils considered for use as dielectric insulating fluids in transformers. Both of these oils are biodegradable and non-toxic which make them attractive for transformer's application, especially considering the increasing concern with regard to environmental issues nowadays. A number of studies had been carried out on PO and CO previously, covering different aspects such as the dielectric, chemical/physical and ageing properties (Abeysundara et al., 2001; Abdullahi et al., 2004; Aditama, 2005; Tenbohlen et al., 2010; Kano et al., 2012; Kurnianto et al., 2012; Banumathi et al., 2013; Azis et al., 2013; Arief et al., 2014; Johari et al., 2014; Suleiman et al., 2014). Concerning the dielectric properties, parameters such as the AC breakdown strength, lightning breakdown strength, dielectric dissipation factor, relative permittivity and resistivity of PO and CO had been examined (Katim et al., 2014; Mohamad et al., 2014; Sinan et al., 2014; Thien et al., 2014). Among the most common PO proposed for applications in transformers is Refined Bleached and Deodorised Palm Oil (RBDPO). Currently, only a few studies have been undertaken to investigate the lightning breakdown performances of RBDPO and CO, especially with regard to the behaviour under different gap distances, polarities and types of electrodes.

Lightning studies can be carried out under uniform, quasi-uniform and non-uniform fields. The uniform and quasi-uniform fields are normally represented by plane-plane and sphere-sphere electrode configurations. These configurations are usually tested to represent the in-service scenarios in transformers (Liu, 2011). Non-uniform field study is carried out to represent an event where a discharge is initiated by an apparent defect in a transformer. Such event can be created by point-plane or point-sphere configurations which can simulate the imperfections that could occur in transformers (Bartnikas, 1994). One of the most important factors

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that can affect the lightning breakdown voltages under a non-uniform field is the polarity of the lightning impulse (Hosticka, 1979; Ushakov et al., 2007). The mechanism of the breakdown in fluid is different under positive and negative polarities. Under a negative polarity, electrons are injected into the fluid if there is a high electrical field to initiate the streamer (Wedin, 2014; Denat et al., 1988). The interaction between the electrons and the molecules in the fluid will cause joule heating and create gas bubbles. If these gas bubbles are long lived, electrons travelling through this channel will acquire more energy to eject more electrons and if the process continues, it will cause an avalanche (Holtzhausen and Vosloo, 2011). Due to the presence of positive space charge, a higher voltage is required to cause the breakdown under negative polarity (Holtzhausen and Vosloo, 2011). On the other hand, under positive polarity, the source of the electrons is obtained from the ionisation of the fluid molecules themselves (Holtzhausen and Vosloo, 2011). These electrons will accelerate toward the positive electrode and further ionisation of the induced positive charge in the gas channel will cause an electron avalanche and streamer propagation (Holtzhausen and Vosloo, 2011; Wedin, 2014; Chadband, 1980).

A number of studies have reported that the lightning breakdown voltages of dielectric insulating fluids under negative polarity tend to be higher than under positive polarity (Mazzetti et al., 1990; Forster et al., 1994; Timoshkin et al., 2009; Liu et al., 2010; Liu and Wang, 2011; Yanchao et al., 2014). In one of the studies, the breakdown voltages of Mineral Oil (MO) under negative polarity can be 60% higher than under positive polarity at gap distance of 5 mm (Mazzetti et al., 1990). Previous study described that in a hydrocarbon fluid such as MO, electrons exhibited greater mobility than positive ions (Schmidt and Pugh, 1977). Under negative polarity, the highly mobility electrons cause smaller contribution of the space charge and higher negative applied voltages are needed for an event of breakdown to occur (Schmidt and Pugh, 1977). For esters, the differences between positive and negative breakdown voltages are lower than MO (Duy et al., 2009, Rongsheng et al., 2009; Ngoc et al., 2010; Wang et al., 2011). In other study, it was observed that the differences between breakdown voltages of MO and esters between negative and positive polarities increased as the gap distance increased (Forster et al., 1994). In addition, it was found that the increment of the breakdown voltage for MO was much steeper under negative polarity as compared to positive polarity as the gap distance increased (Forster et al., 1994; Wang et al., 2011).

In this paper, the influence of voltage polarity on the lightning breakdown voltages of RBDPO and CO under a non-uniform field at various gap distances is investigated. Three testing methods are carried out to test the lightning breakdown voltages. Next, the breakdown voltages of RBDPO and CO are analysed based on a Weibull distribution and compared with MO. Based on the statistical study, empirical formulas for all samples are determined.

2. Material and methods

2.1. Testing fluids and pre-processing procedure

Three samples of RBDPO Olein and one sample of each CO and MO were used in this study. Both RBDPO and CO were obtained from readily available cooking oil products in the market. Table 1 shows the properties of both RBDPO and CO samples. The composition of the saturated, polyunsaturated and monounsaturated fats in all the RBDPO samples are almost the same. The main difference is on the composition of vitamin A and vitamin E where only RBDPOC has vitamin A and the lowest content of vitamin E while RBDPOB has the highest amount of vitamin E followed by RBDPOA. On the other hand, CO does not contain either of vitamin A or vitamin E and mainly consists of saturated fat.

Table 1
Fat, vitamin E/A content of all samples.

Samples(in 100 g)	S. fat (g)	P-U.S. fat (g)	M-U.S. fat (g)	V. E (mg)	V. A (μg)
RBDPOA	44.4	12.2	43.3	50.0	–
RBDPOB	43.0	14.0	43.0	75.0	–
RBDPOC	45.4	11.6	43.0	4.4	264
CO	92.8	3.6	3.6	–	–

S. fat = Saturated fat, P-U.S. fat = Polyunsaturated fat, M-U.S. fat = Monounsaturated fat, V. E = Vitamin E, V. A = Vitamin A.

All samples were first pre-processed by filtering three times through a 0.2 μm pore size membrane filter. All samples were dried in an oven at 85 °C for two days. These procedures were carried out to minimize the amount of particles and moisture that could exist in the sample. Next, all samples were rested further at ambient temperature for one day before tested for lightning breakdown voltage.

2.2. Test setup

Fig. 1 shows the configuration for the lightning breakdown voltage test. A 300 mL transparent perspex cylindrical test cell was fabricated according to the IEC 60897 (IEC 60897, 1987). The test was carried out based on needle-sphere electrodes whereby the tip radius of the copper needle electrode was 200 μm and the diameter of the grounded copper sphere was 12.7 mm. A TERCO impulse generator was used to provide the standard lightning impulse voltage of 1.2/50 μs. All tests were carried out at 2, 3.8, 6, 10, 15 and 25 mm electrode gap distances under both positive and negative voltage polarities. In order to protect the samples and electrodes during the tests, a 2.4 kΩ current limiting resistor was added in the circuit in order to limit the breakdown current. Three testing methods were used in this study, namely rising-voltage, up-and-down and multiple-level.

2.3. Testing methods

2.3.1. Rising-voltage method

The rising-voltage method is normally used for testing different types of voltage including both AC and impulse (Hauschild and Mosch, 1992; Liu, 2011). For a single set of testing, an initial voltage is set and the voltage is increased at a constant rate until a breakdown occurs. The procedure is repeated after a standing time interval of 60 s. In this study, the number of shots applied for each increment of voltage was 1. The initial voltage level was set between 40 kV and 70 kV with a step voltage increment from 2 kV to 10 kV according to the expected breakdown voltage. A total of 15 breakdowns were obtained for each sample.

2.3.2. Up-and-down method

In this method, the initial voltage is set where there is certainty that no breakdown would occur and then increases in steps at fixed amplitude of ΔU until the first breakdown occurs. Next, the same step of ΔU voltage is reduced until no breakdown occurs, and then increases again until the next breakdown. The procedure is repeated until a specified number of breakdowns is obtained (Hauschild and Mosch, 1992; Liu, 2011). The 50% breakdown voltage provides a prior estimate of the mean (Hauschild and Mosch, 1992). In this study, the initial voltage level was set between 40 kV and 70 kV for all gap distances and the step voltages was set from 2 kV to 10 kV according to the expected breakdown voltage. The standing time interval between each breakdown was set to 60 s and a total of 30 shots were applied for each sample.