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Contribution to static electrification of mineral oils and natural esters

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ABSTRACT

A failure of an insulation system of a power transformer can result into an interruption of a power supply and subsequently to a large economic damage. In some cases, the malfunction is so serious that a transformer may explode and catch fire resulting in a direct threat to the life of the device operator. These devices rely on a combined insulation system oil-paper. The oil in a transformer not only impregnates the pressboard paper insulation, hence increases its electric breakdown strength, but also acts as a coolant of active parts of the device. During the cooling, the oil flows in the transformer tank around the core, windings and isolation barriers from hardened paper. At the interface of two dielectrics, the oil and the cellulose in the transformer, electrostatic charges appear. The charges of one polarity are carried in the oil, and the charges of the opposite polarity remain captured in the barrier that is formed by the internal structure of the transformer. The accruing of a certain amount of charge leads to discharges along the surface of the solid insulation and therefore to its partial damage. Ultimately, this can lead to the damage of the whole insulation system of the transformer by its breakdown. At present, the mineral oils are used as the main liquid insulating medium because of their good electrical insulating and cooling properties. On the other side, there is a high environmental burden for their operation and maintenance as well as the subsequent disposal of the discarded oil. The natural esters may be used as a replacement for the mineral oil. They go well with the environment, they are biodegradable and in case of the transformer malfunction, its disposal costs less money.

This paper presents the results of the experiments of electrostatic charging of the mineral oils and natural esters and their comparison. The charging process in the transformer is modelled using a metal cylindrical container with a forced flow of oil using a controlled rotating circular disc from a hardened paper. The results indicate that increasing intensity of friction, increases the electrical charge, which is generated at the interface of the solid phase and the liquid. In these experiments two types of mineral oils were studied. For comparison, two types of natural esters (sunflower and colza oils) were selected and used in the same experiments. The charging of the oils was examined at various temperatures ranging from 25 °C up to 70 °C.

1. Introduction

During repairs of power transformers with an oil insulation system, traces of electrical discharges were found on solid surfaces of the insulation. It was also found that during the operation of these electric devices, processes which cause electrostatic charge generation in the oil insulation occur. Transformer faults caused by static electrification can be traced back to 1970's, first in Japan and later also in other countries. The transformer oil serves as an insulator as well as a cooling medium which extracts the heat from windings and the magnetic core. An electrostatic charge is generated on paper-oil border by a stream of oil flowing around windings and the transformer board. This charge can cause micro-discharges on the surface of the solid insulator. Electrostatic charges accumulate on inhomogeneities of the surface, thus leading to a creation of not equal potentials between different areas of the solid dielectrics. When potentials reach the critical value, partial discharges or electric arc emerge, that damage not only the dielectrics surface but also the oil [1,2].

The electrification mechanism of a liquid flowing around a solid surface leads to the generation of an electric charge on the border of two materials: a liquid and a solid dielectrics. Helmholtz was the first to describe the process of charge generation during the friction of a liquid and a solid dielectrics. It is assumed that at the point of

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contact of two dielectrics a charge is exchanged which leads to a creation of an electrical double layer. This electrical double layer consists of charges with an opposite polarity that are either spread on the surface of the object or in its close proximity. The thickness of the double layer is very small and is comparable to the diameter of several molecules. If two objects with a double layer are separated, the electrical double layer could be split, which results in the objects being polarized. Separation of the objects causes the capacity between objects to decrease, and because the amount of charge stays unchanged, the electric potential quickly increases. Therefore, the two objects stay electrically charged.

A charge generation caused by a flowing liquid alongside a solid surface is depicted in Fig. 1a [3]. A flowing liquid transports the electric charge and leads to its accumulation at the end of the solid surface. Charges can also be accumulated near obstacles alongside their path as depicted in Fig. 1b. A collision with an obstacle can cause, that a part of the free double layer charge can create a moving volume charge. However, immediately behind the obstacle a new double layer is created alongside with a volume charge of an opposite polarity [3].

In transformers, electric charge separation occurs when an oil flows around paper insulation of the transformer windings and in the narrow gaps between transformer barriers. The amount of charge is influenced by several factors: flow speed, temperature, state of insulation, type of oil and quality of oil. In power transformers, the partial discharge often occurs in oil in the upper part of the tank, at the end of the winding. This discharge is caused by an electro-static charge [1].

Insulation oils are characterized by their tendency to static electrification. The static electrification depends on the chemical structure of the oil, on its electrical parameters, temperature, wetting and other factors [4]. Until now, only mineral oils made from a crude oil were used in transformers, but these oils are not very environmentally friendly. Therefore, a replacement amongst natural esters is being sought. Natural ester insulating liquid with its environmental friendliness is the new age dielectric coolant for transformers. It scores over mineral oil in terms of carbon free credentials, fire safety, full biodegradability, lesser aging rate of cellulose, and compatibility with high temperature insulation allowing footprint reduction [5]. When natural esters are used as a replacement for mineral oils it is necessary to know their tendency to static electrification, too. Recently, researchers have focused on comparison of static electrification of natural esters and mineral oils [6–9]. In this area, the influence of interface type of oil-pressboard or oil/paper [7,9], the influence of flowing velocity and oil temperature [6] as well as the influence of dielectric parameters [8] on oil static electrification were studied. The results were not always conclusive, however, in general, it can be said that the charge generation is usually higher in natural ester liquid in comparison with mineral oil. However, the differences observed do not constitute an obstacle to the use of natural ester as a substitute for mineral oil, with respect to the problems and risks associated with static electrification phenomena [9].

2. Measurement setup and specimens

The device simulating the flow of liquid dielectrics on the solid insulator surface was made of a metal tank and a coaxial shielding cylinder. The diameter of the inner cylinder was 100 mm, the diameter of the outer one – 126 mm. The height of both cylinders was 206 mm. The oil volume used for each experiment was 1 L. The motor with speedometer and graphite axis with interchangeable disc of 80 mm diameter was placed on a Teflon pad in order to avoid charge transport from the measurement tank to the active part of the setup.

The schematic diagram for the measurement of the charging current is depicted in Fig. 2. A spinning disc causes a friction between the oil and the solid plate which leads to a charge generation. This charge is continuously accumulated on the metal tank.

The electric current is defined to be the rate at which charges flow across any cross-sectional area. If an amount of charge ΔQ passes through a surface in a time interval Δt, then the average current I_{avg} is given by

$$I_{avg} = \frac{\Delta Q}{\Delta t} \tag{1}$$

In the limit $\Delta t \to 0$ the instantaneous current $i(t)$ may be defined as

$$i(t) = \frac{dQ(t)}{dt} \tag{2}$$

Accumulated charge in the measurement tank during a time period T can be calculated as:

$$Q = \int_{O}^{T} i(t)dt + Q_0 \tag{3}$$

The charge accumulated during disc rotation in oil creates a difference of potentials on the walls of a capacitor. One electrode of the capacitor is represented by the inner measurement tank; the other electrode is created from the outer shielding of the measurement system. Voltage change on the capacitor is defined as:

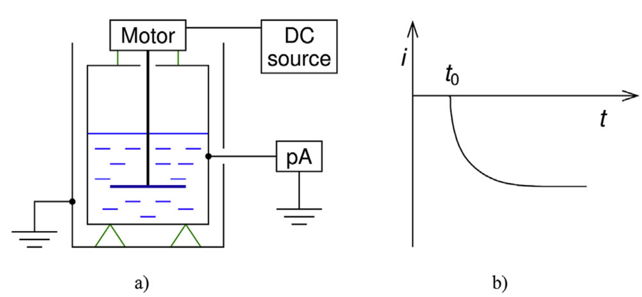

Fig. 2. a) Schematic diagram for the measurement of the charging current, b) time change of the charging current.

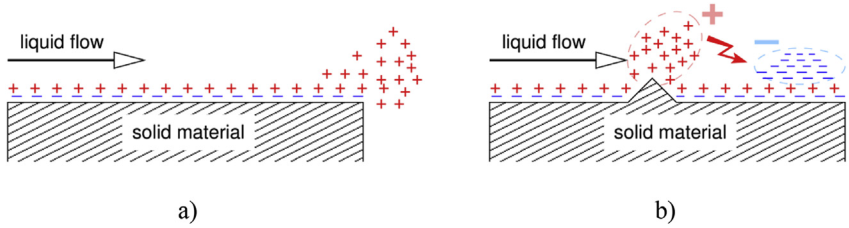

Fig. 1. a) A charge separation of an electric double layer cause by a flowing liquid, b) Charges created on an obstacle with a flowing liquid around it.

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