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Relationship between static electrification of transformer oils with turbidity and spectrophotometry measurements

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ABSTRACT

The paper presents the research results on electrostatic charging tendency (ECT) of transformer oil in a spinning disk system. The measurements were performed at different aging severity. Changes in static electrification were related to some classical aging indexes (conductivity, dissipation factor, water content, resistivity, etc.). Fast, inexpensive and reliable laboratory testing procedures developed by ASTM (D 6802 and D 6181) were also used to monitor the decay products as trace impurities. The obtained results show that static electrification currents increase with temperature, oil flow velocity, coating disk material properties and oil's aging byproducts. The polarity, the amplitude and the time constant of the streaming electrification currents are also affected. This contribution is not only intended to provide a fresh review in this domain of research, but also contains a substantial amount of new material with a view of closing some gaps in the present state of knowledge of transformer oil streaming electrification phenomenon.

1. Introduction

Transformers are key equipments, required throughout modern interconnected power systems. Their insulation system consists mostly of hydrocarbon oil and paper. The solid insulation materials commonly used as wrapping and spacers are cellulose papers and boards made with special care from wood pulps, have to be carefully processed under heat and vacuum to remove moisture and air, before they are impregnated with oil [1,2]. This procedure allowed reducing the water content in the paper down to 0.1%. In practice, the life of a transformer can be as long as 60 years with appropriate maintenance [3]. Practicing engineers currently use a number of modern diagnostic techniques to assess the insulation condition of aged transformers [e.g. 3–7]. To prevent these failures and to maintain transformers in good operating condition is a very important issue for utilities.

In the last decades, static electrification has been recognized as one of the important factors threatening the safety of power transformers [8,9]. The measurement of electrostatic charging tendency in power transformers is as important now as about 15 years ago, when research on static electrification problems began. This phenomenon only occurs when there is relative motion between oil and the surface of the solid insulation when partnered. Such surface can be stationary, as are the pressboard, paper, metal and pipe-work of a transformer or in motion, as are the moving parts of a pump [10,11]. Static charges are produced at the interface solid/liquid flow of oil causing a portion of the electrical double layer formed by preferential absorption of negative ions by the cellulose surface [12,13]. Thus, paper has generally a negative charge and oil positive charge [14]. The static electrification processes are complex and depend on the properties of the oil/solid material interface constituting the electric charge double layer seat and its evolution in time. The characteristics of this latter depend in turn on the condition of oil (aging, moisture, etc.) and the intrinsic properties and surface condition (geometry, roughness, porosity, etc.) of the cellulose paper as well as the external parameters such as the streaming velocity of oil and temperature. Oxidation by-products (peroxide gas, water soluble acids, low molecular weight acids, fatty acids, water, alcohols, metallic soap, aldehydes, ketones, lacquers, and sludges of asphaltene) which change the chemical make up of the oil [15] are also contributing factors.

Because oil is the most readily replaceable element in a transformer, efforts have been made to correlate flow induced failure with oil properties. The influence of the type of solid insulation, the velocity of oil flow, temperature and aging condition of oil and paper (assessed by conductivity/resistivity, dissipation factor, water content, capacitance, turbidity and dissolved decay products content) on the static electrification phenomena is investigated.

2. Theoretical background on the electrification current in a spinning disk system

When a liquid is in contact with a solid (charged or not), the complex liquid–solid system polarizes. The system can be

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considered in equilibrium when there is no more charge transfer at the interface (no current flowing at the interface): the chemical reaction is arrested or considered stationary, offset by leaks to ground via the interface. Any motion of the liquid affects this dynamic equilibrium condition. The physicochemical processes at the interface generates new charges transfer, compensating the convective transport of the diffuse layer, the generated current is also equal to the currents created by the leak and transient accumulation of charges at the interface, the compact layer remaining integral with the interface [10,16]. The streaming current is due to the convection of charge from the layer diffuses into the liquid. It depends on the properties of the double layer: thickness of the diffuse layer, density of space charge at the interface, and the development time of the double layer. The thickness of the diffuse layer is generally equated with the Debye length [16].

The streaming electrification current measurable in a system with a spinning disk in liquid may be described by the following formula [17]:

$$I = \frac{\sigma q_w V}{\varepsilon_r \varepsilon_0 A} + \frac{D_m q_w}{\delta A} S_d - \frac{D_m q_w}{\delta} S_d \tag{1}$$

with

$$A = \frac{q_w}{q_0} = 1 + \frac{\delta V}{\lambda^2 S} \tag{2}$$

The charge penetration depth in the laminar sub-layer is described by the formula:

$$\lambda = \sqrt{D_m \tau} \tag{3}$$

The relaxation time of the charge is expressed as function of the liquid's properties

$$\tau = \frac{\varepsilon_0 \varepsilon_r}{\sigma} \tag{4}$$

The Reynolds number of the flow is determined from the following equation:

$$R_e = \frac{\omega R_1^2}{\upsilon} \tag{5}$$

The shear stress then reads:

$$\tau_w \approx 0.1 R_e^{-0.5} \rho (\omega R_1)^2 \tag{6}$$

The laminar sub-layer thickness is described by the dependence

$$\delta = \frac{11.7\, \upsilon}{(\upsilon / D_m)^{0.333} \sqrt{\tau_w / \rho}} \tag{7}$$

where q_w is the volume charge density at the interface, q_0 the volume charge density in liquid, ε_0, ε_r the free space permittivity and relative permittivity of the liquid respectively, σ the conductivity of the liquid, D_m the molecular diffusion coefficient, V the volume of liquid in the measurement container, R_1 the radius of the disk, $S = S_d + S_c$, where S_d and S_c are the surface of the disk and the surface of container respectively, ρ the density of the liquid, ν the viscosity of the liquid and ω the angular velocity.

3. Experimental arrangement

A laboratory-designed spinning disk system [9] in which the disk is coated on both sides with different cellulose paper (pressboard or kraft paper) is used. This system has been adopted by CIGRE for international comparative measurements of both insulating liquid and solid transformer materials (CIGRE Paper [18,19]).

Various discs, ranging in diameter from 40 to 80 mm were used during experiments. The spinning disk system and the electrometer arrangement are sketched in Fig. 1.

The rotating disk was driven by a 25 W, DC motor having a nominal voltage of 24 V. The rotating velocity of the disk was varied between 100 and 600 rpm by a proportional-integral (PI)-based controller. The container as well as the rotating disk was made of aluminum. The temperature of oil was set and controlled within the range 20–80 °C using a heating system. The electrification currents and the rotation speed measured using an encoder, were simultaneously recorded via a data acquisition. LabVIEW graphical software (version 7.1) was used for the purpose of gathering the current and voltage signal values. The main components of the data acquisition system are a National Instrument DAQ plug-in board (NI PCI-6221) connected to an external box (SBC-68), has a sampling rate between 2400 and 7200 samples/min. The data are stored both as ASCII text files and binary files to ensure further analyses using other software applications.

Due to the centrifugal force, the charges created by the rotating motion of the disk in oil are drained toward the tank wall, where they are collected. The streaming current was measured as leakage current (in pA), to ground from the container using an electrometer inserted between the tank and the ground (Fig. 1).

The electrometer, based on the National Semiconductor LMC6001 BiFET op-amp, had an input resistance 10^{15} Ω and an input bias current not greater than 25 fA. The 1000 MΩ feedback resistor render possible measurements as low as ±5 nA. The 500 kΩ input resistor limited input current to safe levels in cases of significant electrostatic potential on the electrometer input [20]. Two different papers were used to coat the rotating disk: (i) diamond pattern paper 0.62 mm thickness and (ii) pressboard 4.26 mm thickness. These paper samples were vacuumed dried in an oven at 105 °C for 24 h, and then impregnated with dehydrated, degasified naphtenic type I (class A) based inhibited oil for an additional 24 h. To assess the impact of aging on the electrostatic charging tendency (ECT), oil and oil impregnated paper samples were aged in laboratory conditions by placing the specimens in a convection oven at 100 °C and heating them for different periods.

A service-aged oil sample (collected from a Canadian utility company aging power transformers 47 MVA – 161/26.5 kV, commissioned in 1984) was also investigated. In addition to the static electrification, the dielectric properties were assessed with the

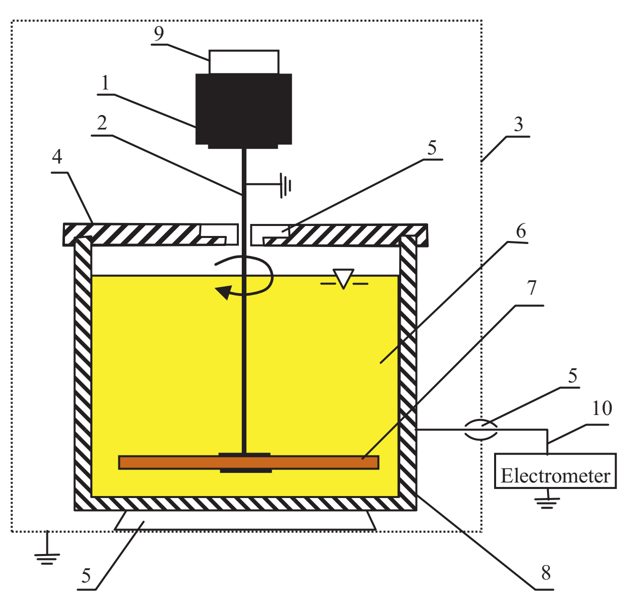

Fig. 1. Diagram of the system with a spinning disk for studying the electrification of insulating liquids: (1) DC motor; (2) rotating mandrel; (3) Faraday cage; (4) cover; (5) insulator; (6) liquid; (7) disk; (8) measurement container (9) encoder, and (10) coaxial cable.