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# Measurement of currents and floating potential in multilayer sensor due to oil-flow electrification

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ABSTRACT

This paper presents floating potential and current measurements due to oil-flow electrification inside a multilayer sensor incorporated in a closed loop filled with fresh transformer oil. All leakage currents at the sensor inlet and outlet, the capacitive current and the streaming current are measured. The waveforms of these currents, floating potential as well as the oil temperature at the sensor inlet are simultaneously recorded for laminar flow and at controlled operating conditions. The measured floating potentials are compared with the calculated ones under different oil-flow velocities and good agreement has been found.



## 1. Introduction

Oil-flow electrification phenomenon in large forced oil-cooled power transformers has been implicated in many field failures throughout the world [1,2]. This phenomenon was mainly investigated by many test facilities, namely, Couette charger [1], open and closed cycles with spinning disc and coaxial electrode system, respectively [3–6], and closed cycles with rectangular oil duct made by pressboard paper [7–11]. Although this phenomenon has been detected in traditional ways using leakage current or potential [1–11], there has been new techniques using Nanosensor [12], electrical capacitance tomography [13] and electrostatic tomography [14] for dielectric property and charge distribution detection.

Generation of charges at solid/flowing insulating liquids interface occurs in the Debye layer as it is generally accepted that it is the transport of charges present in the diffuse layer that is responsible for the electrical double layer (EDL) "rupture". The lack or smaller amount of counter charges in the liquid introduces an imbalance that is compensated by new reactions at the interface generating the streaming current. Depending on the solid phase material, some of these charges accumulate on the solid material, whereas the other entrained charges are transported by the flowing liquid and then accumulate or leak away downstream. This process leads to DC potential buildup, in the same fashion as a Van de Graaff generator, as a result of both surface and volume charges. Hence, erosion and discharges occur on the surface of the solid insulating material. Finally, it may cause major discharge damage as in the case of large forced oil-cooled power transformers, if this generated DC electric field exceeds a critical value. Damage surveys of failed large forced-oil-cooled power transformers revealed some evidence of electrical discharges (electric "tree" paths, "worm holes", presence of carbon and other things) on inner pressboards [15,16]. Actually, the higher the leakage impedance of the pressboards, the more electrically stressed they are. In other words, the charge accumulation on the pressboard can only be limited by either possible chemical saturation of the interface or by leakage and discharges along the interface. This is attributed to the fact that the generated potential gradients become higher than the pressboard dielectric strength [9]. In addition, the recent and the progressive development of compact high-voltage direct current (HVDC) substations has drawn more attention for the importance of studying the oil-flow electrification phenomenon, where oil is used as an insulating medium in converter equipment like transformers, smoothing reactors, filters and bushings [5]. Moreover, several

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explosions and fires in petroleum industry have been attributed to electrostatic charge accumulation in the volume of the flowing fluid leading to the build-up of a DC electric field. This occurs during transporting, processing and storage of various types of hydrocarbons, where discharge through the vapor phase causes an explosion hazard [17].

In this paper, the floating potential measurement due to oil-flow electrification is investigated by using a multilayer sensor in a closed loop of fresh transformer oil. The factors affecting the following currents: streaming, capacitive, middle electrode, and those at sensor inlet and outlet as well as the floating potential are introduced and discussed.

## 2. Experimental setup

The experimental setup (flow loop device) has been built at the University of Poitiers in collaboration with "Electricité de France (EDF)" to simulate the oil path along the pressboard between transformer windings [10,18]. Fig. 1 illustrates the construction of the new sensor. It consists of two 300-mm length oil ducts of rectangular cross-section (30 mm × 1.85 mm) and each made of 2 mm thickness pressboard sheets stuck together and inserted in a polytetrafluoroethylene (PTFE or Teflon) enclosure. A middle copper plane electrode (250 mm × 50 mm × 1 mm) wrapped by Kraft (two layers with thickness ≈ 0.24 mm) separates these two oil ducts. Two stainless steel plane electrodes (260 mm × 50 mm × 0.1 mm) have been placed facing the largest external surfaces of the pressboard duct beyond 2 mm PTFE for electrical insulation. This configuration intends to represent the pressboard parts inside power transformers, which have high leakage impedance with regard to imposed potential areas (windings and tank). It is worth mentioning that the middle copper plane electrode can be grounded or energized by a floating source (battery) or a high-voltage direct current (HVDC) source.

The leakage currents at the sensor inlet and outlet ($I_i$ and $I_o$), the capacitive "accumulation" current ($I_c$), the generated current from middle copper plane electrode ($I_g$), and the streaming current ($I_s$) current are measured by means of four electrometers Keithley 610C and one electrometer Keithley 6514. In addition, the current due to

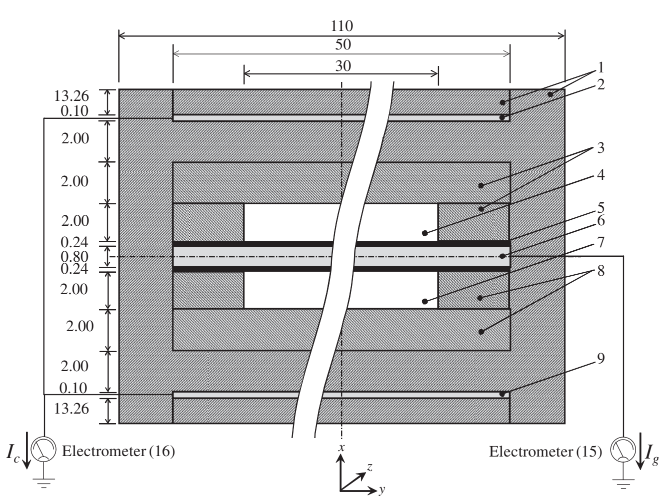


**Fig. 1.** Schematic cross-sectional view of the multilayer sensor (rotated 90° clockwise). All dimensions are in mm. 1: PTFE enclosure (300 mm × 110 mm × 40 mm), 2: left grounded stainless steel plane electrode (260 mm × 50 mm × 0.1 mm), 3: pressboard paper (thickness ≈ 2 mm), 4: left oil duct (300 mm × 30 mm × 1.85 mm), 5: wrapped Kraft (two layers, thickness ≈ 0.24 mm), 6: energized copper plane electrode (250 mm × 50 mm × 1 mm), 7: right oil duct (300 mm × 30 mm × 1.85 mm), 8: pressboard paper (thickness ≈ 2 mm), and 9: right grounded stainless steel plane electrode (250 mm × 50 mm × 0.1 mm).

the accumulated charges on the middle copper plane electrode ($I_g$) is measured in the case of grounded electrode, see Fig. 1. In this case, one electrometer is used because $I_i \approx I_o$ and they are very small compared to the other measured currents. For floating potential measurements, the Keithley 610C electrometer is used.

## 3. Results and discussion

### 3.1. Behavior of current waveforms

The leakage currents at the sensor inlet and outlet ($I_i$ and $I_o$), the capacitive "accumulation" current ($I_c$), and the streaming current ($I_s$) current are measured for the floating middle copper electrode case as shown in Fig. 2a. While these currents as well as the generated current from middle copper plane electrode ($I_g$) are measured for the grounded middle copper electrode case as shown in Fig. 2b. Typical waveforms are shown in Fig. 2 at $T = 20$ °C and $u_m = 0.6$ m/s, where the test is started by 100 s without flow, followed by flow for 900 s and finally no flow for 600 s. The idea behind recording an initial interval of 100 s is make sure of discharging the sensor and the streaming current vessel. In addition, a preconditioned of the sensor is conducted by supplying a 50-Hz sinusoidal voltage of 10 V (peak–peak) between the middle copper electrode and the two outer steel electrodes. This applied bipolar voltage speeds up the neutralization of any accumulated/trapped charges inside the sensor.

It is found that the instantaneous sum of the steady-state values of the streaming current, the currents at the sensor inlet and outlet ($I_i$ and $I_o$) and the capacitive "accumulation" current ($I_c$) for the floating middle copper electrode case is approximately equal to the

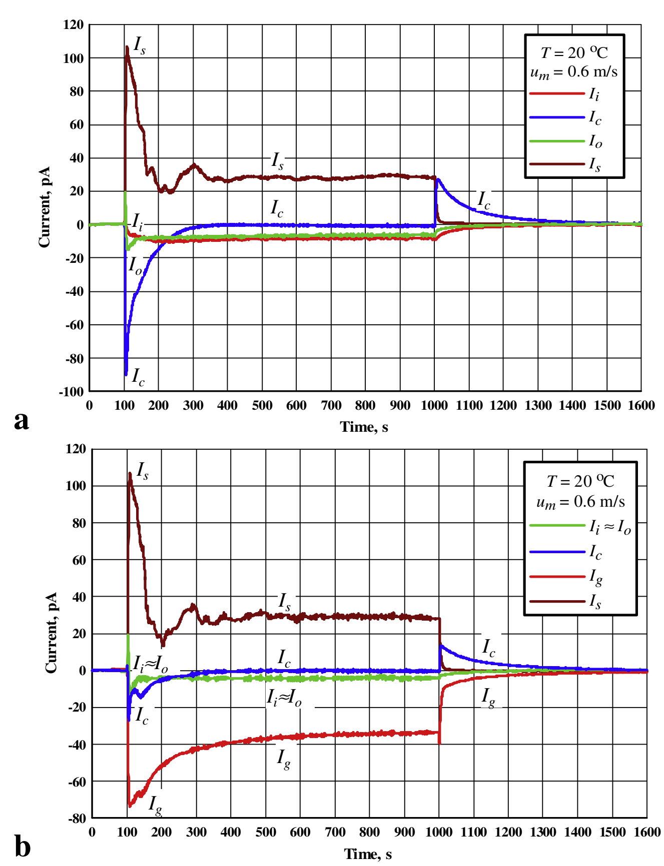


**Fig. 2.** Current waveforms for (a) the floating and (b) the grounded middle copper electrode at $T = 20$ °C and $u_m = 0.6$ m/s.