High Power Transformers Failures due to Flow Electrification: Tools for Understanding the Electrostatic Hazard.

T. Paillat, J. M. Cabaleiro, M. El-Adawy, O. Moreau, G. Touchard.

***Abstract*—Flow electrification phenomenon is suspected to be responsible for some failures in high power transformers. Acoustic sensor surveys from suspected transformers and visual observations in damaged transformers revealed some evidences of electrical discharges (electric "tree" paths, "worm holes", presence of carbon ...) on inner pressboards. Nevertheless the scenario, which lays the electrostatic activity and consequently transformer failure, is still not well understood. The goal of this work is to propose some elements for understanding electrostatic hazards in high power transformers.**

Experimental set up has been developed in our laboratory to study flow electrification of oil at a pressboard rectangular duct. As in power transformers, the oil/pressboard couple is insulated from the ground by an oil volume. Pressboard potential, accumulated charges on pressboard surface are recorded and correlated to charge leakage.

***Index Terms*—Electrical double layer, Flow electrification, Physicochemical reaction coefficient, Streaming current.**

I. Introduction

As soon as a liquid is in contact with a solid, the initially neutral system becomes polarized under physico-chemical reactions (adsorption, corrosion) at the interface. According to the Stern Model the charge distribution leads to an electrical double layer made up of a compact charge layer at the interface where electrical strengths keep electrical charges close to the solid wall, and a diffuse charge layer in the bulk of the liquid. The global system will be considered in equilibrium (diffuse layer established) when the flux of charge at the wall is equal to zero. As the charges in each layer have opposite signs, the solid/liquid system always remains electrically neutral.

The flow electrification phenomenon is due to the convection of the diffused layer charges. The liquid flow leads to substitute a dynamic equilibrium for the previous static equilibrium. This process is observed by the apparition of wall currents. If the solid duct or the liquid tank are dielectric solid or conductive solid insulated from the ground, electrical potential of the solid increase. It could be enough to produce some electrostatic discharges.

During the seventies in Japan and more recently in the different countries, electric manufacturers and utilities began to suspect the static electrification to be responsible for failures in power transformers. In high power transformers, pressboard and oil are required for electrical insulation. On the other hand, the oil is also used as a coolant of the system. The flow electrification process occurring at oil-pressboard interface seems to be responsible of these electrostatic incidents. After damage, surveys revealed some evidences of electrical discharges (electric tree paths, worm holes, presence of carbon ...) on inner pressboards [1-3](Fig. 1).

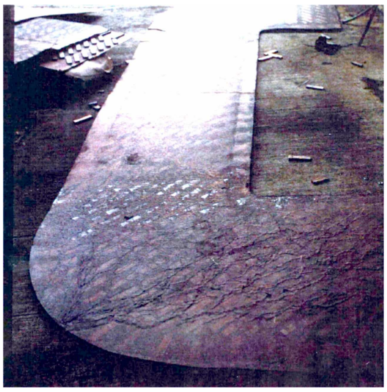

Fig. 1. Electrostatic discharge at pressboard surface coming from damage power transforming.

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II. Analysis ofthe electric equilibrium

A. *Experimental set up*

Experimental sensor has been developed in LEA laboratory to characterize flow electrification phenomena for an oil/pressboard couple in a used transformer. The facility was developed a few years ago as a part of the research program of "Electricité de France" and the University of Poitiers. It allows measuring the accumulated charge occurring in a flow electrification phenomenon on pressboard duct (for our experimental geometry) directly proportional to the solid potential.

The device consists of a closed circulation loop where a liquid flows through a sensor [4]. The sensor consists of a rectangular channel, which is inserted in a P.T.F.E. frame.

Two plane electrodes are placed facing the external surfaces of the pressboard duct, beyond 2 mm of P.T.F.E., to measure a mainly capacitive current (Iaccumulation) related to the charge trapped inside the pressboard (accumulation charges). In addition to the leakage of the solid charge takes place towards two stainless steel couplings placed at both extremities of the channel, and insulated from the rest of the loop by P.T.F.E. flange couplings. This leakage is probably favored by the modification of electrical conductivity in the electrical double layer at the solid/liquid interface.

Typical experimental results obtained with these facilities are presented in Fig. 2. We can observe upstream and downstream leakage currents, and accumulation current as a function of time during flow. The sum of these currents is equal and of opposite sign to the streaming current measured by a relaxation tank placed at the exit of the sensor. In this experimental condition, the accumulation charge (integration of an infinite time of the accumulation current) is about 10^{-10} to 10^{-8} C, depending of the oil/pressboard couples studied).

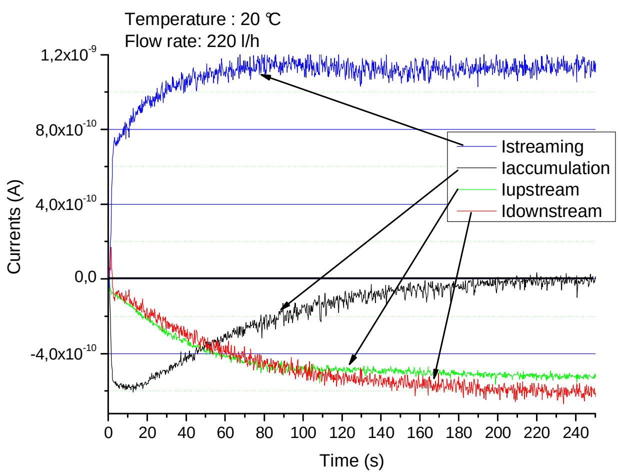


Fig. 2. Typical currents measured on the sensor for “low leakage impedance” configuration.

The pressboard potential is about 1 to 100 V. It is not sufficient for produce some electrostatic discharges.

This measurement conveys that the accumulated charges reaches a maximum value depending on an electrical equilibrium between charge induced at the interface and leakage path in ground direction [5]. Electrical analogical circuit could be proposed for modeling this phenomenon as shown in Fig. 3. The charge separation mechanism is compared to current generators. The π type array of resistances and capacitors represents the solid (pressboard-P.T.F.E.) and the interface. In this circuit, the potential of the solid is controlled by the magnitude of current generators, the magnitude of the leakage resistance values and the electric capacitive values of the solid.

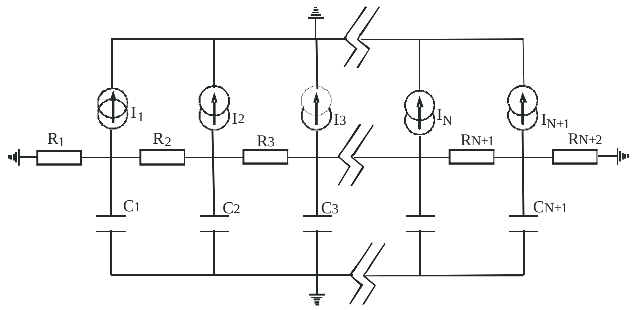


Fig. 3. Electrical analogical circuit proposed to model flow electrification phenomenon on dielectric solid surface. I_N are the different current generators and R_N the leakage resistances and C_N the capacitive values distribute all along the duct.

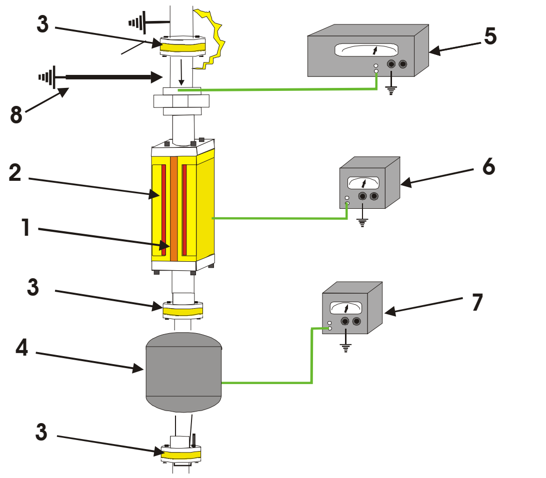
B. *Electrical Discharges observation*

Increasing the pressboard leakage resistance increase the solid potential. Inlet and outlet leakage measurements have been disconnected from the set up. The only electric leakage path for the solid accumulate charge pass through oil bulk.

During this so-called “high leakage impedance” configuration, charge accumulation in the pressboard, streaming current and floating potential of the inlet tube are monitored (Fig. 4).

In this configuration, for two couples involving suspected oils, some electrical discharges have been observed in air around P.T.F.E. upstream flange coupling (Fig. 4). This discharge phenomenon has been observed among more than 30 couples which have been studied till now with this sensor protocol [6].

To study the discharge phenomenon, a needle has been placed in the air at about 2 mm from upstream P.T.F.E. flange. For an oil flow rate of 350 l/h, the streaming current, the accumulation charge and the potential on upstream inlet tube flange have been recorded. For the used oil /used pressboard, it turns out that electrical discharges have appeared between the needle and the P.T.F.E. flange when the inlet tube potential reached a value of 3.4kV, corresponding to an accumulated charge equal of 820nC. Without any needle, the electrical discharges have occurred when the inlet tube potential has reached to 11.5kV while the charge accumulation in the pressboard was five times greater than the accumulation level for the “low impedance leakage” configuration (2800 nC



1 Pressboard duct	5 Electrostatic Volt meter(solid voltage)
2 P.T.F.E frame	6 Pico ammeter (accumulation current)
3 P.T.F.E flange	7 Pico ammeter (streaming current)
4 Relaxation tank	8 Needle for discharge

Fig. 4. Electrical discharges in air for "high leakage impedance" configuration

instead of 48nC).

From Fig. 5, it clearly appears, that the electrical discharges coincide with the positive peak of the accumulation current: the electric charges trapped close to the pressboard interface quickly relax to the ground.

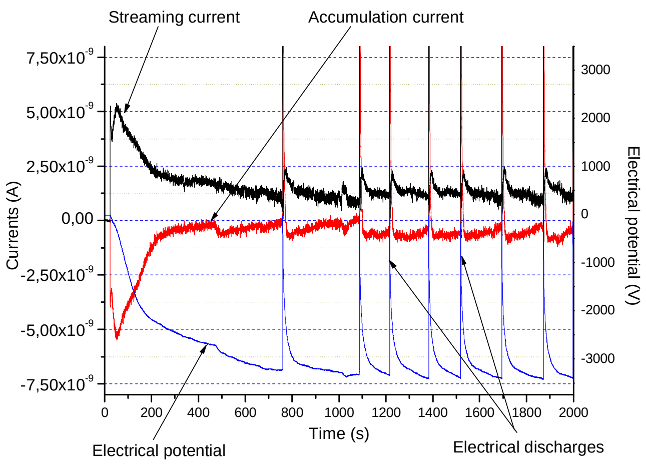


Fig. 5. Inlet tube potential, accumulation and streaming currents for "high leakage impedance" configuration.

In the goal to increase the electric potential on pressboard surface for an oil flow, a new device is developed in the laboratory. This new configuration is representative of a well insulated part of pressboard inside big transformers. Indeed, in the bottom of those transformers, an area exists, near the 45° region, where part of pressboard are submitted to impacting flow and with leakage paths is very long. In damaged power transformers, some electric tree paths were observed in this region [1-3].

This set up has been developed for respecting two conditions respecting the 45° region.

- pressboard electric insulation is carried out by the oil volume.
- the laminar oil flow is locally perturbed for increasing the sheering stress.

III. New Experimental Device

A. Experimental description

The well-insulated duct is a rectangular channel of 1.5 m long made from P.T.F.E. A pressboard channel of 1.4 m length is inserted in it (Fig. 6). The inner dimensions of the pressboard channel are 6×30 mm^2. The pressboard used has 3 mm thickness. As in power transformers, some pieces of pressboard (obstacle) are introduced in the duct for controlling the oil flow. The sensor is connected from the rest of the circulating loop by two insulating tank (inlet and outlet). They are cubic, 50×30×30 cm^3 which are made from P.M.M.A. and filled with oil. The extremities of the duct are placed in the middle of these insulating tanks. The only leakage path for accumulated charge of the pressboard surface is the 20 cm of oil bulk.

Accumulation current (and accumulated charges) could be measured by 2 electrodes, face each side of the pressboard channel. They located at 70 cm from the entry of the duct. They are made of stainless steel, 60 mm in diameter and totally included in the P.T.F.E. Nevertheless, they increase the electric capacity of the sensor and affect the local electric potential. During experiments, when the accumulated current is not measured, the electrodes are extracted from the sensor.

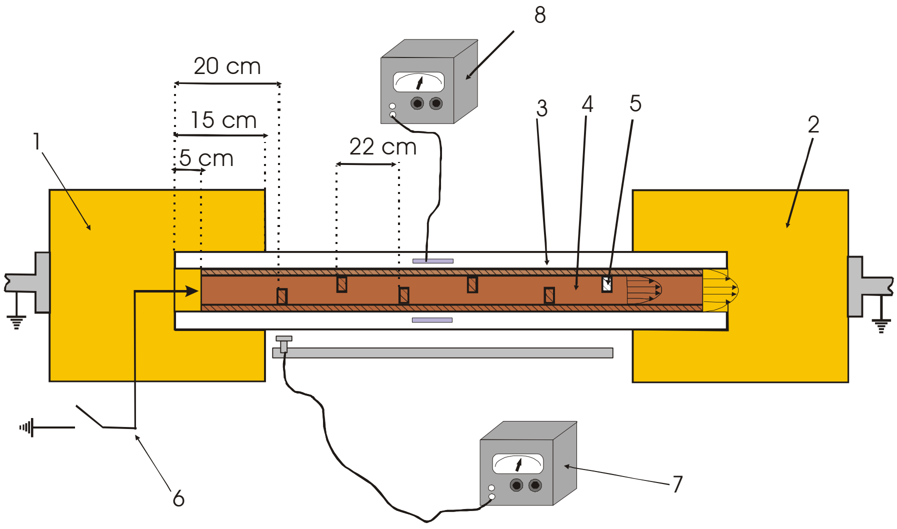
Electric potential at the inlet solid surface is estimated by electrometer field 177A Monroe which allows reducing the influence of apparatus in the electric properties of the sensor. The used probe is 20kV/cm. It is placed in air at 2 cm facing the external surfaces all along the sensor. A mechanical system for moving this probe along the sensor between the inlet and outlet insulating tank has been added to this device.

For all the experiments, a new pressboard duct made from Kraft pulped, used in high power transformer, is studied. Also, different oils are tested, new oil and used oil coming from aged power transformer.

B. Analysis of potential measurement and accumulation current.

Figure 7 presents the accumulation current and the electric potential at the external surfaced of the sensor versus time. Even if these two measurements were made at different positions on the sensor, but they all have both the same dynamic. The charge accumulation is stopped when the P.T.F.E. potential reaches a maximum magnitude (in absolute value) corresponding to the electric equilibrium value. In fact, these two measurements are directly proportional to the electric potential at the oil/pressboard interface:

- The capacitive value of the equipped sensor with the accumulation current electrodes and cables measurement is estimated about 200 pF



1 Inlet insulating tank
2 Outlet insulating tank
3 P.T.F.E. frame
4 Pressboard duct
5 Obstacle in pressboard
6 Needle inserted in inlet tank
7 Electro field meter
8 Accumulation current measurement

Fig. 6. The new configuration device for study electrostatic hazards

- Considering the dielectric rigidity of 3mm thickness of pressboard impregnated by oil (3), and 2mm thickness of P.T.F.E. (2.1) the electric potential at the oil/pressboard interface the surface could be estimated by calculation about 1.3 higher than external pressboard potential.

According to accumulated charge measurements gives in Fig. 6, the interface potential could be estimated about 7.5 kV with the current measurements and 19 kV with electric field measurements. It seems to be, that all current data usually induced a lower estimation of interface potential than electric field meter. It is probably due to the included electrodes.

However, this difference seems to be constant. For laminar flows, versus the Reynolds number, the accumulated charge and the potential on the external surface of the P.T.F.E increase in the same way (Fig. 8).

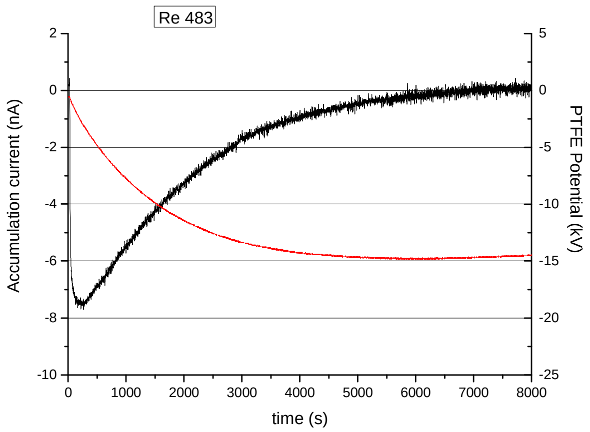


Fig. 7. Correlation between accumulation current and P.T.F.E. potential measurements versus time for constant Reynolds number Re 483.
Accumulated charge : 1.56 10^{-6} C.

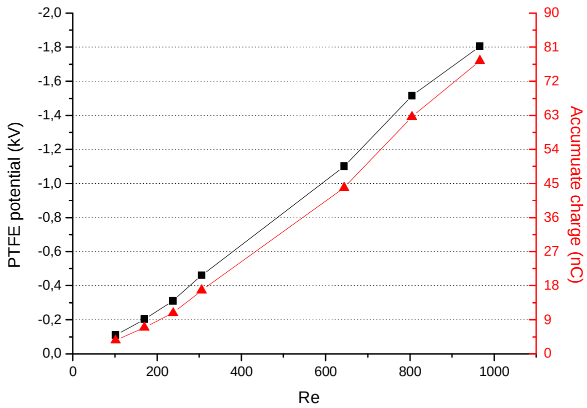


Fig. 8. P.T.F.E. potential measurement and accumulate charge versus Reynolds number.

C. Electric potential distribution of P.T.F.E. along the pressboard.

The analysis of the P.T.F.E. potential distribution along the pressboard duct is presented in Fig 9, 10 and 11.

Different oil/pressboard ducts are studied.

- new oil with duct equipped without obstacles ;
- new oil with duct equipped whit obstacles; (oil conductivity : $0{,}62\times10^{-12}\ \Omega^{-1}m^{-1}$);
- used oil coming from used transformer with duct equipped without obstacles. (oil conductivity : 4,16 $10^{-12}\ \Omega^{-1}m^{-1}$).

For these measurements, capacitive electrodes are not placed in the set up.

Experimental results show relatively little differences between the different oil/pressboard duct couples. The potential seems to be constant in the middle of the duct. It is higher at the both extremities of the duct in particularly with used oil. This behavior is quite surprising. For a dielectric solid like transformer pressboard which could be modeled by electric circuit (Fig. 3), the maximum potential is typically expected in the middle.

More, the effect of these obstacles is surprising too. Recent investigations [7,8] have shown that the shearing stress increasing flow electrification process. These obstacles which are introduced in the duct, modify the flow profile and then increase the shearing stress. Globally, by comparing Fig. 9 and Fig. 10 for the same velocity, the potential measurement with duct equipped with obstacle, induces higher potential than duct without obstacle. But locally, obstacles don't induce maximum value of the potential.

Used oil circulating in the pressboard duct has produced the higher value of the PTFE potential. At the entry of the duct, it reaches 15kV for a Reynolds number 483. Nevertheless, this value is not sufficient for inducing electrostatic discharge in the oil. Indeed the dielectric breakdown value of oil is about 20kV/mm.

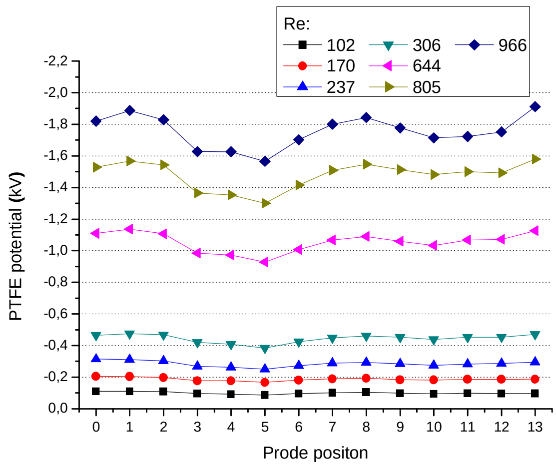


Fig. 9. Map of PTFE electric potential for new oil and duct without obstacles for different Reynolds numbers.

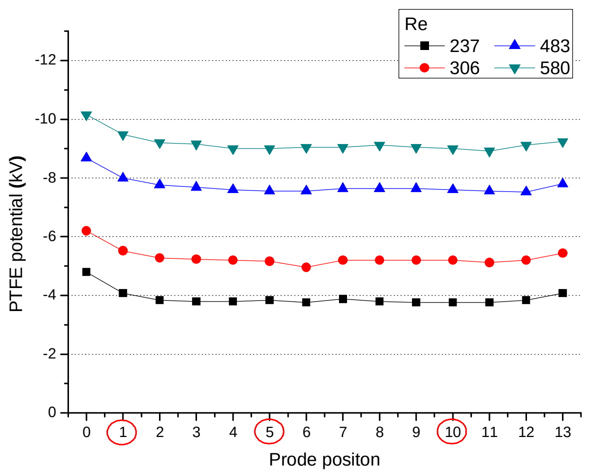


Fig. 10. Map of PTFE electric potential for new oil and duct equipped with obstacles for different Reynolds numbers. Probe positions 1, 5 and 10 are corresponding to position of the flow obstacles.

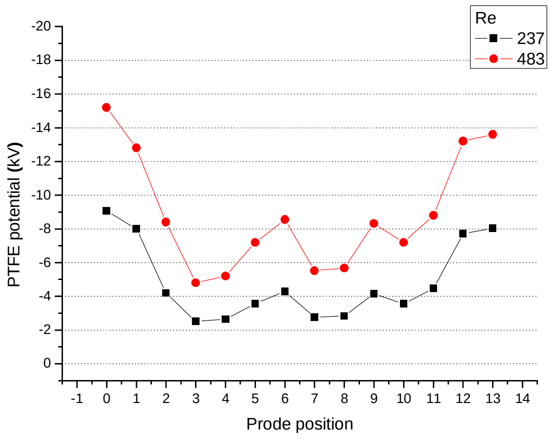


Fig. 11. Map of P.T.F.E. electric potential for used oil and duct without obstacles for different Reynolds numbers

D. Analyze of potential measurement and accumulation current when electrical leakage path is introduced.

For studying the charge leakage at the oil/pressboard interface, a stainless steel needle is placed in the inlet insulating tank, facing the entry of the pressboard duct, near 2 mm from it (Fig. 6). The needle is controlled by mechanical switch which allows to ground it or to keep it in floating potential. The Electric potential on the needle is measured by electrometer field 177A Monroe. Also, the accumulation current and the electric potential at the entry and the exit of the duct are measured. They are recorded versus time and presented in Fig. 12.

The oil flow is induced for reaching equilibrium values of the potential along the pressboard duct (phase 1). The stainless steel needle is in the floating potential position. It takes an electric potential about -19 kV due to probably the liquid flow on it surface or to the influence of pressboard potential. As the duct is in equilibrium, the accumulation current is equal to zero and the potentials are constant, about -18,5 kV at the entry and -15 kV at the exit.

In phase 2, the stainless steel needle is in the ground position and its potential is zero. It induces a decreasing P.T.F.E. potential (in absolute value) and a positive accumulation current. This decreasing potential is more important at the inlet (18.5 to 17.5 kV) than outlet (15 to 14.3 kV). But it seems, more the measurement is far from the inlet, more the time reaction is increasing. While the decreasing potential at the entrance P.T.F.E. duct seems almost simultaneous, it is delayed at the exit. It seems that in ground position steel needle allows a new path for pressboard accumulated charge to leak. The electric field is not enough producing electrostatic discharge (we have never observed some discharge in oil) so it is more probably a conduction phenomenon which allows this charge leakage and a new space charge distribution in pressboard. It appears that all the conduct is affected by this new charge distribution induced by this new electric leakage path. But the effect is smaller when the distance from the leak increases.

Finally in phase 3, the stainless steel needle is in floating position again. After delay, depending on the measurement position on the duct comparing to the entry, the different potentials increase (in absolute value) for reaching their equilibrium value obtained in phase 1. Accumulation current becomes negative corresponding to a new charge generation at the interface for balance charges which have leaked in phase 2. After a short time, it comes to zero corresponding again to equilibrium state found in phase 1.

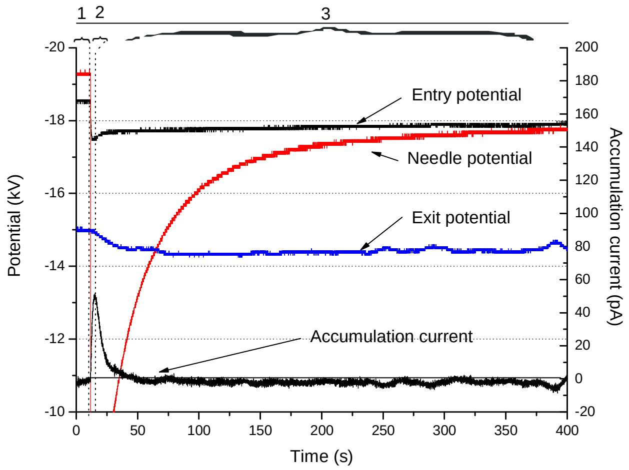


Fig. 12. Potential and current measurements versus times (Re 237)

IV. Conclusions

Electrostatic in high power transformer is responsible of various failures. After damage, electric tree paths in these power transformers revealed some evidence of electrostatic activity in 45° zones. Nevertheless, the script with lead these activities to the destructive breakdown appearing in power transformer still not understood. In order to reproduce electrical condition in 45° zones new set up has been developed in laboratory in Poitiers. It is loop where oil flow through of pressboard duct of 1.5m long. Although that the pressboard was very insulated by a volume of liquid , and the presence of obstacles in oil flow which increase sheering stress, the pressboard potential does not allow to produces some electrostatic discharges in oil. Probably that oil/pressboard couple used for these studies are not sufficient for produce some charges.

However diverse information is published. Electric potential seems to be constant all along the pressboard duct except at these extremities. A new charge organisation in the pressboard, probably by conduction is induced when electric insulation of the solid/liquid interface is changed. More, although the shearing stress is clearly identified as a factor increasing the production of charges at the solid/liquid interface, the adding obstacle in the conduct did not increase the local electrical potential at the surface of the pipe.

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