Electrostatic Hazard in High Power Transformers : Analyze of ten years of the Capacitive Sensor

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***Abstract* -- In high power transformer, oil flowing on pressboard surface is suspected to be responsible of electrostatic hazards and failures. Different methods of risk assessment have been proposed to understand and prevent it : ministatic tester in the Westinghouse protocol, ministatic tester in the spinning disk measurement, monitoring of tangent delta and dissolved gases measurement... At P' institute of Poitiers an original sensor was developed used for quantification of the electric charge generated and of accumulated charge for an oil flow onto the surface of a transformer pressboard insulated from ground. Operational for 10 years, this bench has been used to study over a hundred couples of oil / pressboard, pairs of new oil and pressboard, pairs of aged oil and pressboard, pairs of suspicious oil and pressboards…. The paper presents a comparative analysis of these 10 years of experience. This analysis provides, among other results, a critical electrostatic hazards assessment in transformers and an attempt of discrimination tentative of a suspected transformer**

***Index Terms*—Flow electrification, hazard, power transformer.**

I. Introduction

WHEN a liquid is in contact with a solid, a physical chemical phenomenon creates a charge separating process called "electric double layer" which polarized the solid/liquid interface. Electrically charged species of one sign are created at the solid surface while opposite-sign species are distributed within the liquid. If the solid is a dielectric or an insulated conductor, charges may accumulate. If a liquid flow is involved, liquid charges are transported which enables new charge separation process at the interface and increases the local electric potential in the solid. This flow electrification phenomenon is causing various electrostatic hazards in industries.

For the last thirty years, static electrification has been suspected to be responsible for power transformers failures. Damage surveys revealed some evidences of electrical discharges (electric "tree" paths, "worm holes", presence of carbon ...) on inner pressboards [1-2]. In fact oil flow at the pressboard surface leads to the electric double layer, on one hand to a space charge in the oil which can relax in contact with grounded metallic walls, and on the other hand to a space charge in the pressboard which is accumulated.

In the 1990s, EDF faced the static electrification phenomenon on some generator power transformers. Besides defining corrective actions for in-service equipment, EDF has sought to characterize preventively the most common couples of oil / pressboard and the impact of maintenance operation on the phenomenon [3]. This concern led EDF to favour the emergence of characterization methods of generation and accumulation of charge with the University of Poitiers on new and used materials. Similarly EDF characterizes macroscopically the behaviour of any new transformer design by measuring the leakage current after each temperature-rise test

In the case of dielectric liquids flowing through metallic or insulating pipes, it seems that the flow electrification phenomenon is mainly due to the impurities existing in the liquid [4-6]. In high power transformers, the phenomenon is highly more complex because the pressboard is not a single component but it constituted of several components, which may induce different physico-chemical reactions with the oil impurities. More, the aging of power transformer components (pressboard, oil, copper…) due to temperature and moisture contribute influencing the flow electrification phenomena. Indeed, it seems that flow electrification might generate a surface charge, which would induce electrical discharges at the pressboard-oil interface, which then enhance the phenomenon. The results showed that the space charge density was multiplied by three or four when the pressboard has been degraded by electrical discharges. This conclusion was alarming because it seemed that a chain reaction might happen inside the power transformer, until its failure [7].

Nowadays, the ECT (Electrostatic Charging Tendency) measurement in the Westinghouse protocol [8] and, to a smaller extent, the continuous aging test for tanδ are the most commonly applied measurements for operating transformer monitoring. Previous study has shown that these two oil parameters are not really reliable with regard to the charging process [9-10]. When transformer oil seems suspect with regard to these two tests, a third diagnostic measurement is also recommended: the leakage current. It consists to measure the current resulting from flow electrification, collected on the windings of the unloaded transformer. These normative measurements allow characterizing insulating material but do not allow evaluation of the electrostatic hazard.

They were about ten years ago, in the P' Institute of Poitiers University (called LEA Laboratory at that time) with the collaboration of EDF, an experimental sensor call the capacitive sensor has been developed. This sensor is based on the accident analyses in high power transformers in which electric discharges were observed at pressboard surface for very well insulated parts of transformers. Thus, for oil flows, the capacitive sensor allows estimating the accumulated charges on a pressboard surface (directly correlated to the local potential) for a geometry and for an experimental protocol systemically applied. The goal of this paper is to present about ten years of capacitive sensor measurements for the prediction of electrostatic hazard in high power transformers.

II. EXPERIMENTAL MEASUREMENT DESCRIPTION

A. *Capacitive sensor description*

A stainless steel loop (Figure 1) has been developed to simulate the oil path along the pressboard between the windings inside a transformer [10]. Oil flows through a sensor duct (6) which enable us to measure accumulation and generation parameters. Oil temperature (2) and oil flow rate (3) are controlled in the loop. The sensor (figure 2) consists of a rectangular pressboard channel (3*30 mm2 cross section, and 300 mm in length) inserted in a PTFE frame. Two stainless steel electrodes have been placed facing the largest external surfaces of the pressboard duct embedded in the PTFE frame. Connected to a pico-ammeter, these electrodes allow measuring the accumulation current (7) due to the charge trapped on the pressboard surface. The upstream and downstream leakage currents (8-9) are linked on the inlet and outlet stainless steel elements which are insulated from the rest of the loop by PTFE flanges coupling. Moreover, the charge carried by the liquid flow is relaxed in the relaxation vessel (5). The resulting measured current on this vessel is the streaming current also called the generating current (10). In the first version of the sensor only the accumulation current was measured. The interpretation of measures gradually led to complete the loop with the addition the three additional current measurements.

The loop consists exclusively of materials inert to mineral oils as stainless steel, glass and viton in order to avoid any chemical reaction and oil pollution.

B. *Experiment protocol*

In order to allow a comparative analysis of all oil/pressboard pairs studied on the sensor, an experimental protocol is systematically reproduced. The loop and pressboard duct are dried by nitrogen gas flow before being submitted to vacuum (0.01 mm Hg) for 24 hours. The filling of the equipment is then made also under vacuum by direct transfer from commercial tanks. Finally oil flows in the loop for about 2 hours with a bulk pressure on 0.2 bar to impregnate the pressboard duct. In addition, a 24 hours relaxation period is always applied before starting the experiment campaign.

The measurement session is organized on two or three consecutive days. They included an oil temperature cycle (20-10-20-40-60-80-20°C) representative of different operating conditions of the transformer: start-up, operation, over-heating. More, this temperature cycle allows observing parameter evolution after heating and cooling. For each temperatures, three laminar oil flow rates (132, 220, and 308 l/h), leading respectively to mean velocities of 40, 68 and 95 cm/s are experimented

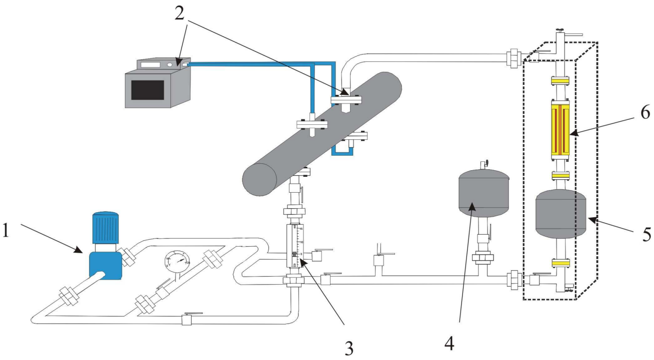


Fig. 1. Test loop to simulate oil flow (1 Pump, 2 Heat regulation, 3 Flow meter, 4 Oil tank , 5 Relaxation vessel , 6 Capacitor sensor).

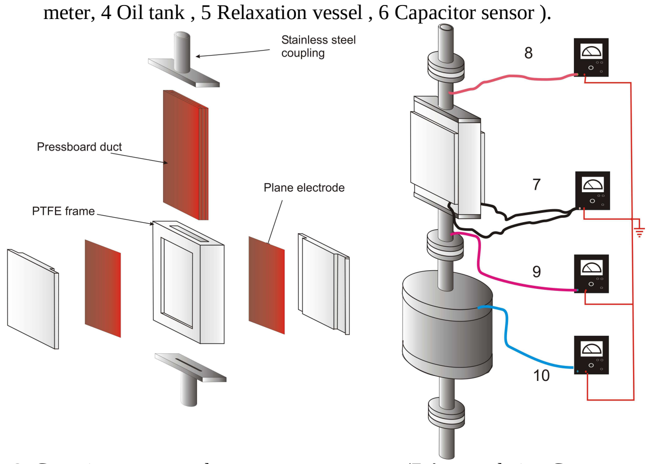


Fig. 2. Capacitor sensor and current measurements (7 Accumulation Current, 8 Upstream leakage current, 9 Downstream leakage current, 10 Streaming current (generating current)).

C. Experiment protocol

Figure 3 shows a typical evolution of current measurements versus time. The sign of the currents given by the figure 3 is representative of the majority of the different oil/pressboard pairs studied. At the exception of a few pairs, including silicone oils for example, currents related to pressboard charges, accumulation current, upstream and downstream leakage currents are negative, the current associated with the oil, streaming current is positive.

As soon as the oil starts to flow, a charge is generated at the interface. Positive charges in the fluid (oil) are transported by the flow and induced the streaming current which passes by a maximum value and reaches a steady state. In the same time, opposite charges are trapped inside the solid pressboard. The magnitude of the accumulation current increases and come back more or less rapidly to zero. The surface potential increases, until reaching a steady state leakage current toward the grounded duct outlet and inlet through paths along the interface. The dynamic of the transient state, the magnitude of the streaming current and the maximum value of the accumulation current depend on the oil/pressboard pair. It can be checked that the sum of the leakage (inlet and outlet), accumulation and streaming currents is equal to zero.
Characteristic parameters considered as relevant with regard to flow electrification have been measured for several combinations of (new and used) oil/pressboard pairs.
The studied parameters are:

- Charge accumulation, obtained from integration versus time of the accumulation current,
- Steady state generation current.

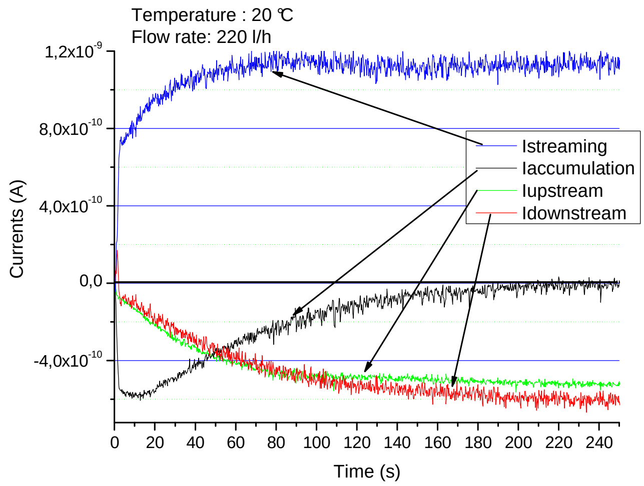


Fig. 3. Typical currents measured on the sensor for "low leakage impedance" configuration

D. Electrical equivalent circuit

Electrical equivalent circuit allows representing this measurement system. (Figure 4). The physicochemical phenomena at the interface which created the solid charge is assimilated to current generators distributed along the solid/liquid interface. The streaming current due to the convection of the liquid charges is equal but opposite of the current generation. The magnitude of these generating currents is decreasing from the duct entry due to the electrical double layer development along the interface. Resistor components are correlated to charge leakage in inlet and outlet pressboard duct. The resistor interface is linked to the electrical properties of the solid/liquid interface modified by electrical double layer charges. Finally, capacitors are associated to solids (pressboard, PTFE, electrical cable) and liquid permittivity property. They are considered as constant along the duct.

Considering this circuit, the solid potential directly proportional to the solid accumulation charges depends on the generating current magnitude and the electrical properties of the solid/liquid couple.

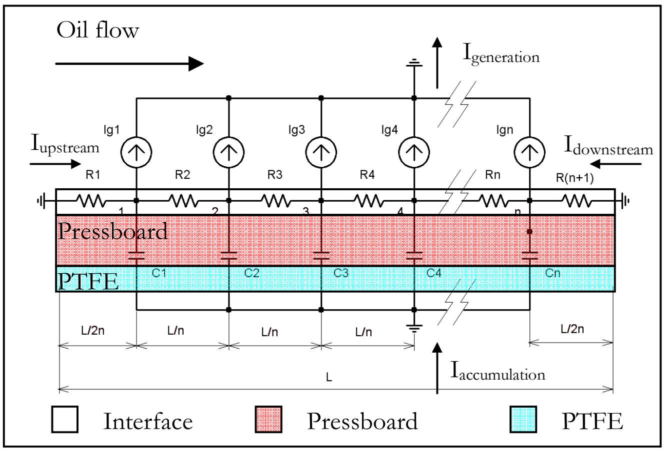


Fig. 4. Electric equivalent circuit

E. Oil/Pressboard pairs

Over 100 pairs have been appraised on the sensor with different objectives:

- Qualification of new products ("standard pair"): oils (or pressboards) marketed by the oil industries are constantly changing their chemical composition for economic and technical reasons, some oils are disappearing as new products are marketed. All these developments require to determine the physical properties of these oils such as electrostatic behaviour before use in power transformers.

- Monitoring the aging and maintenances of operating transformers ("standard pair"): for operating transformer, the dielectric materials evolved chemically versus time and may require technical operations such as oil reconditioning or regeneration, maintaining the oil level in the transformer by adding of new oil or more simply by changing it. The expertise of the oils concerned about the sensor can then assess the impact of these operations on the electrostatic behaviour.

• Contribute to monitoring suspected transformers ("suspect pair"): the presence of dissolved gases in oil, electric discharge activities detected by acoustic sensors are all factors suggesting an electrostatic hazard in a transformer. Some pressboards and oils coming from these transformers have been studied for contribute to their supervision. For the following of the document, a pair will be qualified as "suspect pair") if at least one of the dielectrics (pressboard, oil) is coming from a suspect transformer.

• Tools for studies of electrostatic behaviour ("research pair"): the chemistry of pressboards and oils play an important role in the electrostatic risk. In order to study it, pressboard chemistry perfectly controlled and specially designed, oils containing additives such as BTA, have been studied on the loop for the understanding of electrostatic mechanisms.

III. Analyse of Results

A. Experimental results

The Figure 5 and 6 present respectively the charge accumulation (in absolute value) on the pressboard surface versus oil resistivity at different oil temperatures for about 100 oil/pressboard pairs. Overall the accumulated charge is always negative. It fluctuates over three decades of 0.1nC to 100nC. Some rare pairs lead to values lower or higher. Regarding the current generation (Figure 7 and 8), the current is changing globally between 10 and 1000pA with some exceptional lower or higher values. While it seems clear from the figures that increasing the conductivity increases the current generation, the link between the accumulated charge and the conductivity is much less obvious. Indeed, the increase in ionic impurity concentration has two opposing effects. It stimulates chemical reactions at the interface and therefore increases the current generation but at the same time, facilitates electric charge leakage at the interface because of the increase in conductivity. Thus, the value of the accumulated charge is a compromise between these two mechanisms. Nevertheless, it seems that the impact of conductivity is more important on the current generation than on the charge leakage, as, mainly the charge accumulation seems to slightly increase with the conductivity.

The temperature effect on the liquid is substantially equivalent to the liquid resistivity. Namely, it stimulates the production of charges, but at the same time increases the electrical conductivity of the oil. Thus, the charge accumulation behavior versus temperature is quite similar (Figure 5 and 6). It seems to give values slightly higher at 20°C than 60°C. However, our experience shows that this observation must be balanced. Indeed, the new oils seem to lead to the charge accumulation values slightly higher at 20°C than 60°C, for used oil the conclusion is not so evident. Thus the average value of all the data is 25.1 nC at 20°C whereas it is only 12.3 nC at 60°C.

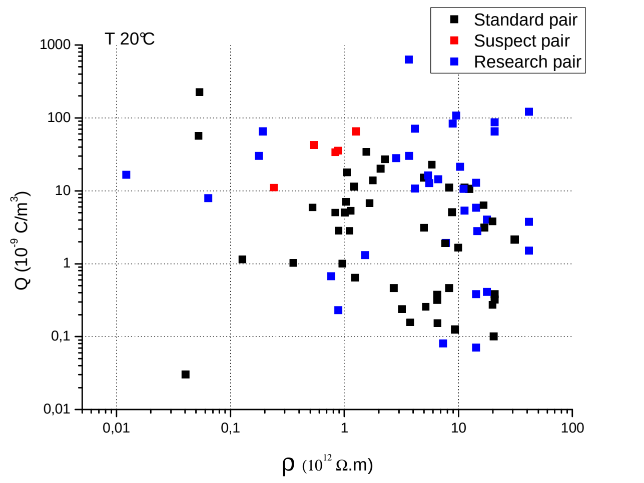


Fig. 5. Charge accumulation on the pressboard surface versus oils resistivity (temperature 20°C, flow rate 220l/h).

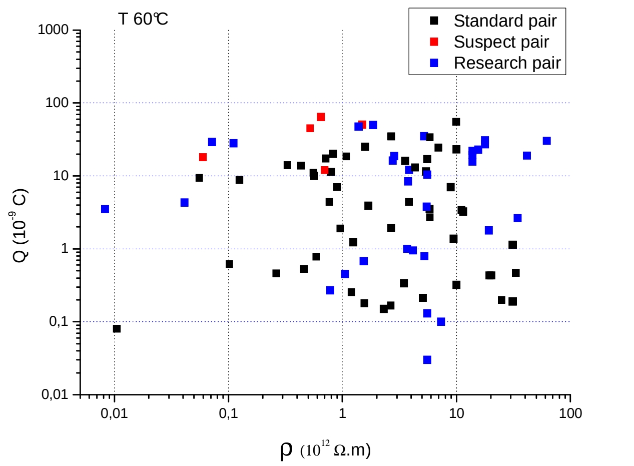


Fig. 6. Charge accumulation on the pressboard surface versus oils resistivity (temperature 60°C, flow rate 220l/h)

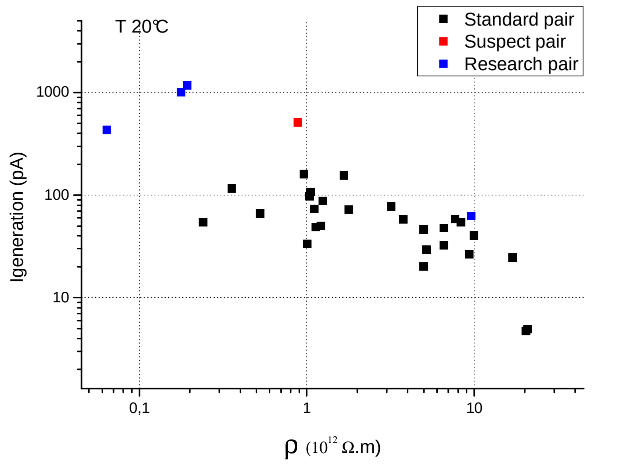


Fig. 7. Current generator versus oils resistivity (temperature 20°C, flow rate 220l/h).

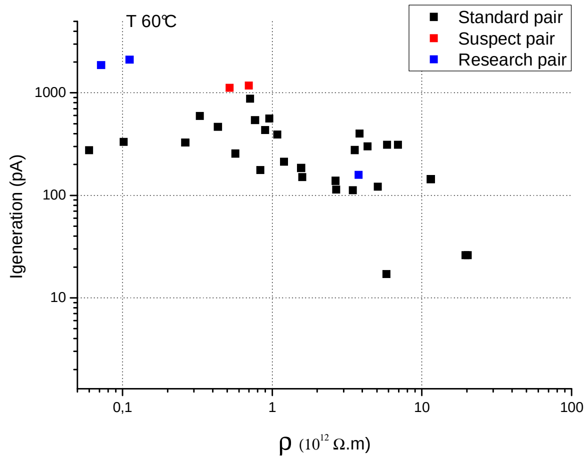


Fig. 8. Current generator versus oils resistivity (temperature 60°C, flow rate 220l/h)

B. *Discussion*

It seems more relevant for electrostatic hazards analysis to approach the actual operating transformers, focusing particularly on an operating temperature (60°C) and oil/pressboard pairs likely to be present in the transformer thus to exclude all research pairs. For these couples, the accumulated charge is presented (Figure 9) versus the electrical resistivity of the oil. Only couples including new and used oils are given (excluding oil blends). They are distinguished by an empty symbol for used oils and full for new oils. Considering the Figure 9, it seems globally that the space charge is increasing with aged oils. Thus the average value of all the data is 10.9 nC for used oil when it is only 7.28 nC for new oil (9.0 nC for used oil when it is only 5.6 nC at 20°C), which corresponds to an average increase of the charge in the time of the order of 49.7% at 60°C (60.7% at 20°C). In confirmation, we had the opportunity to follow the aging of a transformer in operation. For three times, the oil coming from one transformer was studied in the loop with a new pressboard of the same nature : when the fresh oil is introduced in transformer, after 2 and 5 years of operation. Thus the measured charge accumulation values are chronologically : 0.5, 4 and 24 nC (at 60°C). If in addition we consider the increase in load over time of the charge generation by the transformer (fully confirmed by the ECT measurements and the current generator measurements), the aging of transformers could be a criterion which would aggravate the electrostatic hazard. However, only rare transformers have developed electrostatic accident even after several decade of operation and, some accidents were observed on "young" transformers.

The second element that appears in Figure 9 is related to the results obtained with the couple described as suspicious. The values of the accumulated charge are among the highest of Figure 9. The criterion of the accumulated charge seems to be satisfactory to identify a dangerous situation. However a suspect pair leads to values of accumulated charge high but without reaching remarkable values. This pair consists of an oil from a transformer in which an abnormal rate of hydrogen was observed. It remained in operation for several years until its withdrawal from the electricity network.

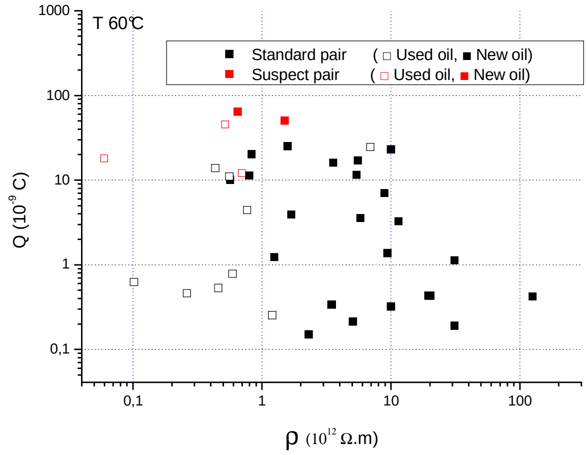


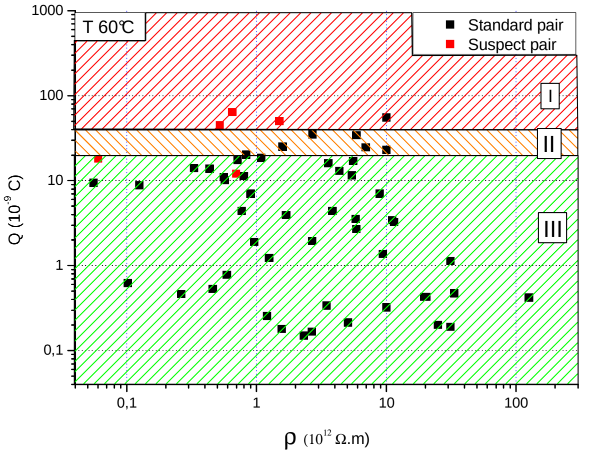
Fig. 9. Charge accumulation on the pressboard surface versus oils resistivity (temperature 60°C, flow rate 220l/h).

IV. Conclusion

The discussion seems to show that the charge accumulation on surface pressboard allows estimating the electrostatic hazards in high power transformers. On this basis, a graph of hazard expertise (Figure 10) based on the value of the accumulated charge versus the oil resistivity was developed. It considers three areas regardless of resistivity. An area described as suspicious (I), suspicious since there is a hazards that in this area the transformer develops an electrostatic activity. An area where the operation (III) of the transformer is quite safe with respect to electrostatic hazards and finally between the two, an intermediate area (II) with a different reading according if the oil/pressboard pair is new or used. In the construction of graph two choices were realized and assumed, on the one hand the geometry of the separation areas on the other hand on the threshold values of these areas.

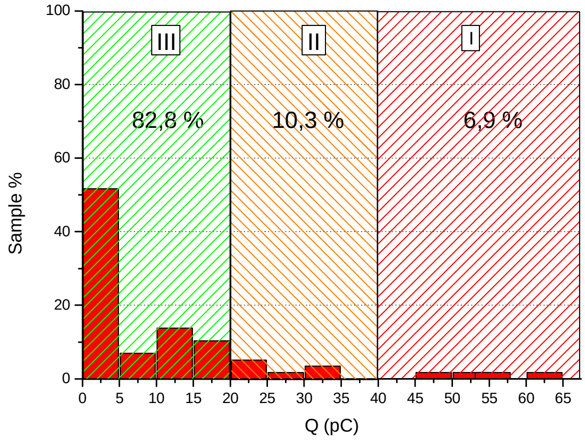
As stated in the equivalent circuit, the accumulated charge reflects a balance between the charge generation (current generation) at the oil/pressboard interface and the leak of these charges. The electrical conductivity of the oil and pressboard contributes to establish the equilibrium values of the accumulated charge and the potential. In addition, Kotho and all [12] have chemically and electrically analysed used oil coming from about hundred operating transformers. The number of operation years of the transformer increases the oil conductivity while the oil breakdown voltage seems to be independent. More generally, the impact of the electrical conductivity on the rupture is not so significant [13]. Thus it does not seem appropriate to bring up a criterion of oil resistivity in the choice of area construction in the graph (Figure 10).

Three suspect pairs lead to values of the accumulated charge clearly higher than the other studied pairs (Figure 9), they must be included in suspicious area. However, the electrostatic events in the power transformers are rare or exceptional and therefore marginal compared to the number of transformers in operation. Given these two elements, we assume as lower threshold limit of the suspicious area, an accumulated charge of 40 nC. Under these conditions, 6.2% of the couples studied belong to the suspicious area (Figure 11). This value is probably a little excessive in relation to the number of transformers which has developed an electrostatic activity, but it could be explained by the deliberate choice of those suspect pairs. By granting a safety margin of 50%, ie a value of accumulated charge of 20nC, the higher limit of the safe operation area is then established. More than 80% of oil/pressboard pairs are then in the safe operation area (Figure 11). This 50% margin which delimits the intermediate zone, allows one hand to overcome the uncertainty regarding the critical value of the accumulated charge. On the other hand, it also introduced the dielectric material aging, since the average increase in the accumulated charge due to aging is 50% (at 60 ° C). The materials of a new transformer, whose accumulated charge is in intermediate zone, have a probability to reach the critical value of accumulated charges with years.



I Suspicious Area ; II Intermediate Area ; III Safe Operation Area

Fig. 10. Charge accumulation on the pressboard surface versus oils resistivity (temperature 60°C, flow rate 220l/h).



I Suspicious Area ; II Intermediate Area ; III Safe Operation Area

Fig. 11. Sample distribution versus charge accumulation (temperature 60°C, flow rate 220l/h)

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