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Study of DC Conduction in Aged Transformer Oil under Non-Uniform High Fields

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This paper emphasizes experimental results of DC conduction in aged transformer oil using point-plane configuration. The effects of oil dehydration and filtration, anode material and field strength are investigated and discussed. It is found that *i–t* and *i–E* characteristics display exponential behaviour and tunnelling phenomenon, respectively. Moreover, sample preparation and anode/liquid interface play an important role in explaining the mechanism of DC conduction under non-uniform high field.

Introduction

The conduction of current at high field is considered one of the important dynamic events [1–3] leading to electrical breakdown. Many processes and variables are involved and their interaction are not fully explained. Most of the investigations carried out by various workers during the past few years discussed a number of hypotheses responsible for current conduction. Of equal importance is the study of the metal/liquid interface which controls electron injection and collection; and also the effects of viscosity, density, purity of liquid, and electrode geometry are indispensable factors [3–6]. The dynamics of the non-uniform current instabilities is also a question which still needs interpretation [2]. It has been reported [3] that most of the studies have been confined to fields less than 25% of breakdown and other few studies using spherical electrode configuration which is not simulating the practical conditions in service.

This paper investigates the phenomenon of conduction in aged transformer oil under high field, near to breakdown. A point-plane configuration is employed which produces a highly divergent field and simulates actual service conditions. Experimental results are presented and discussed for the effect of oil dehydration, filtration, anode material and field strength.

Experimental

Aged oil was sampled from an outdoor 100 MVA, 115/66 kV Transformer fitted with a silica gel breather and oil conservator, with a maximum oil temperature rise of 55 °C. This unit has been operating without any fault for the last 5 years, in a refinery area located in the desert but not far away from the sea coast. Ambient temperatures vary from 0-47 °C and relative humidity ranges from 60–70%.

The oil test samples were dehydrated by passing them through a one-meter-long chromatographic column containing non-adsorbent silica gel. After dehydration, both oils were filtered separately through sintered glass filter size 4, porosity 5–15 μm(F4) and size 5, porosity 1–2 μm(F5). The materials used for plane electrodes were brass (Br), copper (Cu), nickel (Ni), the electrodes having 25.4 mm diameter and 10 mm thickness with edges rounded. Brass electrodes were nickel plated to get nickel electrodes. They were mechanically polished using diamond paste on a rotating disc fitted with green wool cloth, and using alumina as a lubricant. A mirror finish was achieved until no pits or scratches were seen under a magnification of 200. The point electrode used was a steel sewing needle of tip radius 25 μm. The test cell and the electrode assembly were washed thoroughly with petroleum ether every time

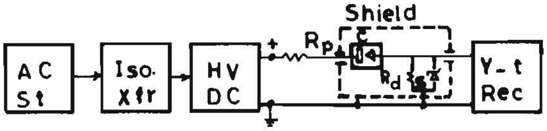

Fig. 1: **Experimental Set-Up: R_p—Protection Resistor; R_d—Detection Resistor; S—Surge Arrester; C—Test Cell.**

the electrodes or oil were replaced and subsequently immersed in n-haptane and subjected to ultrasonic energy for 30 min. After cleaning, the test cell was dried inside an evacuated desiccator containing silica gel for about 15 min.

The schematic diagram for the experimental set up is shown in Fig. 1. The electrode gap was fixed at 0.75 mm, and the positive high field was applied to the plane electrode, the field not exceeding 80% of the DC dielectric strength of the oil sample. The point electrode remained connected to the ground in all experimental observations. Every possible measure and precaution were taken to minimize leakage current and extraneous interference. Conduction currents were then recorded for 15 min. duration after the application of voltage for each case. Before each measurement, the sample was conditioned by short circuiting and grounding the electrodes for about 60 s.

Results and Discussion

I. Effect of Dehydration and Filtration

The time dependence of the quasi-steady conduction current in a time period 10–600 s and for aged oil sample using different anode material is shown in Fig. 2–4. It is clear that, generally, the current decreases with time lapse linearly on a log–log plot, indicating electrical purification [4, 7] which is in agreement with previous similar findings in the case of sphere–sphere configuration [8]. The conduction current, i, during the time lapse, t, after the application of the field could be expressed by the genearl formula: $i = Kt^{-n}$ ($10\,\text{s} < t < 600\,\text{s}$), where k and n are constants depending on the electrode material of the anode and on the degree of filtration. The range of the exponent, n, is $0 < n < 1$ except in a few cases where it is very near to zero, or less than zero. A close observation of the recorder chart in these particular cases reveals that the current exhibits an increase in the quasi-steady state value following the sudden occurrence of a large duration burst. This burst may result in an increase in the number of charge carriers due to the increase of impurities by electrical partial discharge [9].

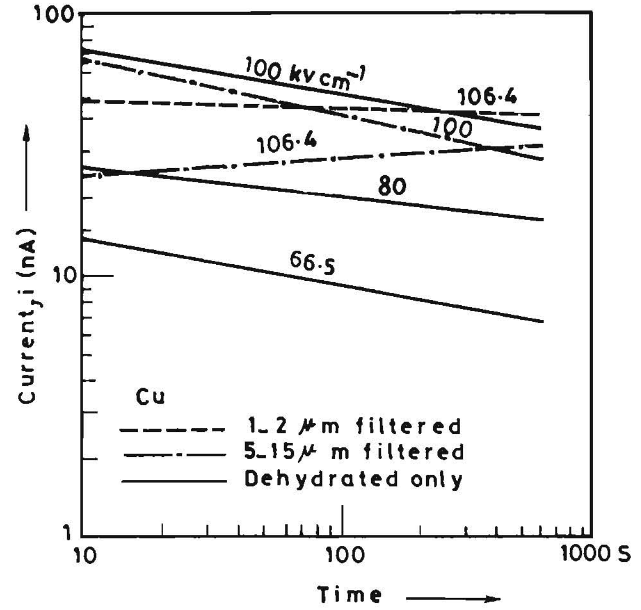

Fig. 2: **Effect of the Degree of Filtration on i–t Characteristic for Aged Oil, Using Copper Anode.**

Figures 2–4 also illustrate the effect of dehydration (D) and filtration through sintered glass filters of porosity 5–15 μm (F4) and 1–2 μm (F5). It is found that the relative magnitude of the conduction current using F4 is larger than when using F5. The introduction of filters increases the current as compared to

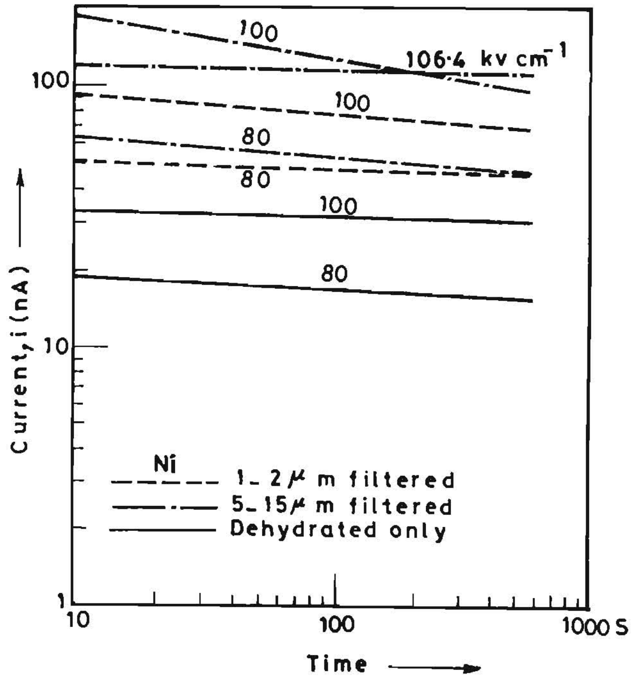

Fig. 3: **Effect of the Degree of Filtration on i–t Characteristic for Aged Oil, Using Nickel Anode.**

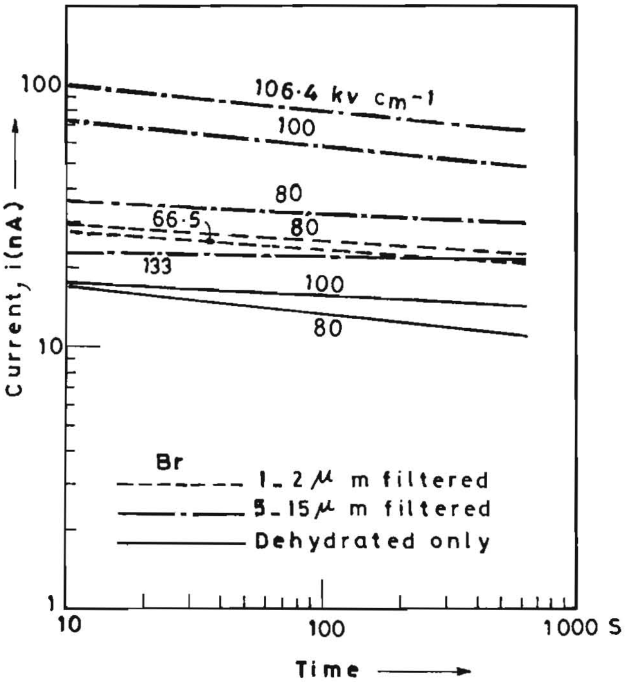

Fig. 4: Effect of the Degree of Filtration on *i–t* Characteristic for Aged Oil, Using Brass Anode.

the results after dehydration. These observations are independent of time lapse and the material of the anode. The increase of conduction after filtration as compared to after dehydration is contrary to what is expected, as the solid impurities and moisture have been partially removed. This contradiction may be explained by the fact that the aged oil is a non-homogeneous mixture as a result of the oxidation products produced by polymerization and condensation during service aging. Filtration will partially remove these products and hence the oil becomes more homogenized with less density and high relative fluidity. Consequently, the conduction current increases when the filters are used in service aged oil.

II. Effect of Anode Material

Figure 5 illustrates the effect of anode materials on the conduction current in an aged oil sample, filtered with F4. It was observed that the nickel electrode exhibited higher current, such that Ni > Br > Cu. This relation holds good for field strength in the range of 80–106.4 kV cm^{-1}. It is also interesting to note that the order of this inequality in a non-uniform field conforms to the electronic work function of these metals. However, a different inequality has been reported for the sphere–sphere configuration [8].

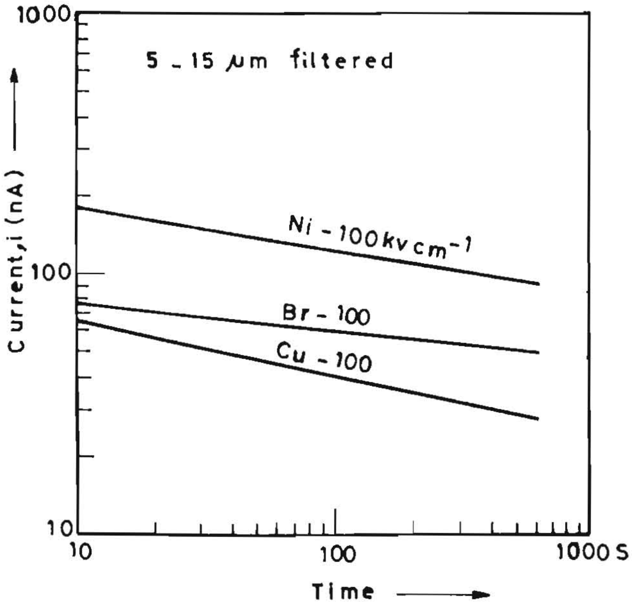

Fig. 5: Effect of Anode Material on *i–t* Characteristic for Aged Oil, Using 5–15 μm Filter at 100 kV cm^{-1}.

Figure 6 shows this effect in a fresh oil sample, filtered with F4. The results here are found to be field strength dependent. For instance, the relation is Br > Ni > Cu at 93.3 kV cm^{-1}, but as the field increases to 106.4 kV cm^{-1} the relation changes to Cu > Ni, and it becomes Ni > Br at 120 kV cm^{-1}. This means that for fresh oil in the field strength range

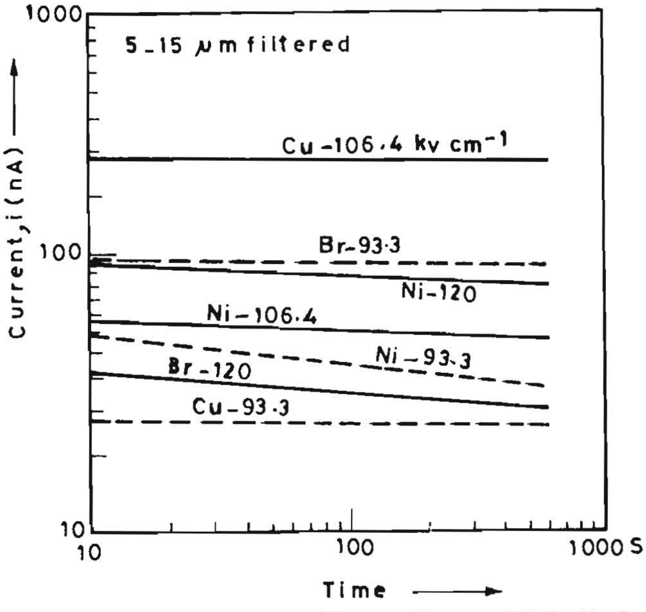

Fig. 6: Effect of Anode Material on *i–t* Characteristic for Fresh Oil, Using 5–15 μm Filter at 93.3, 106.4 and 120 kV cm^{-1}.

93.3–120 kV cm^{-1}, the variation of conduction current with field strength is not monotonous, Fig. 6. A similar phenomenon has been reported in *n*-hexane in the field range 350–650 kV cm^{-1} [10]. These observations reveal that the effect of anode material on conduction current is field dependent in the case of fresh oil, but field independent in aged oil. It is likely that the highly stressed metal/liquid interface at the anode is playing an important role in charge collection and hence the process of conduction. Comparison of the two oils indicates that as the aged oil has been subjected to a long period of discharges occurring in it, polymerization [11] and increase in charge transfer complexes [12] result in enhancement of charge carriers and the establishment of a more stable anode/liquid interface than the one in fresh oil. Moreover, the larger amount of charge carriers in aged oil result in a stronger local field at the anode.

This indicates that in aged oil, ionization due to electron collision and dissociation of molecules plays a stronger role in conduction by masking the electronic emission from the cathode and hence further increasing the importance of the metal/liquid interface.

III. Effect of Field Strength

Figures 7–9 shows the field dependence of the conduction current under a non-uniform field for brass, copper, and nickel anodes at 10 s, 100 s, and 600 s. For the brass electrode (both oils) at the time lapse of 10 s and 600 s, it was found that current/voltage relation is non-linear at electric field strength from 80–120 kV cm^{-1}, Fig. 7. As the field strength increases, the current in fresh oil starts decreasing to a minimum, and then increases sharply with further increase in field strength. For the nickel electrode, the behaviour of conduction current in aged oil is similar to that for the brass electrode, but in fresh oil the current increases linearly with the applied electric field in the range of voltages of our experiments, Fig. 8. The effect of anode material on the *i–E* characteristic at 100 s was derived from Fig. 2–4 and shown in Fig. 9, indicating a similar phenomenon as illustrated in Fig. 7 and 8. Such a minimum in the *i–E* characteristic has also been observed recently in *n*-hexane at fields in the range 350–600 kV cm^{-1} [10]. It is interesting to note that this minimum modifies the 'Nikuradse' ideal characteristic and some other experimental results [6, 13]. Moreover, the distinctive

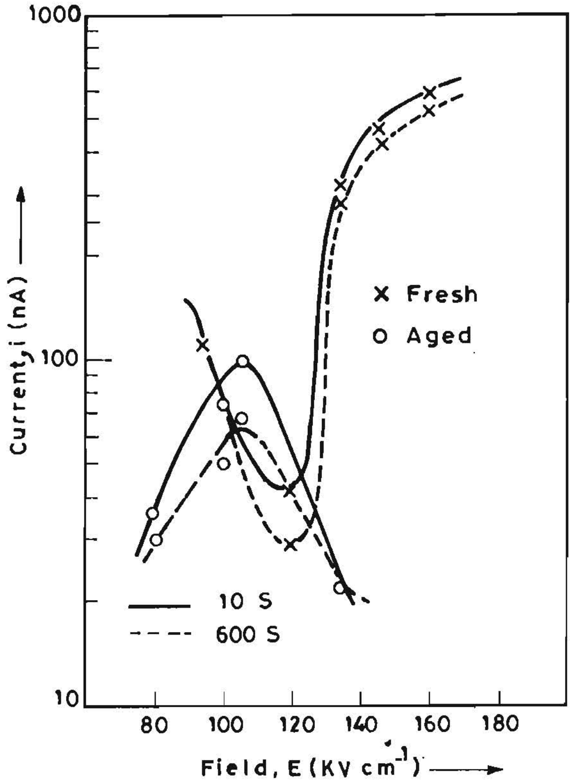

Fig. 7: **Field Dependence of Conduction Current at 10 s and 600 s, Using 5–15 μm Filter and Brass Anode.**

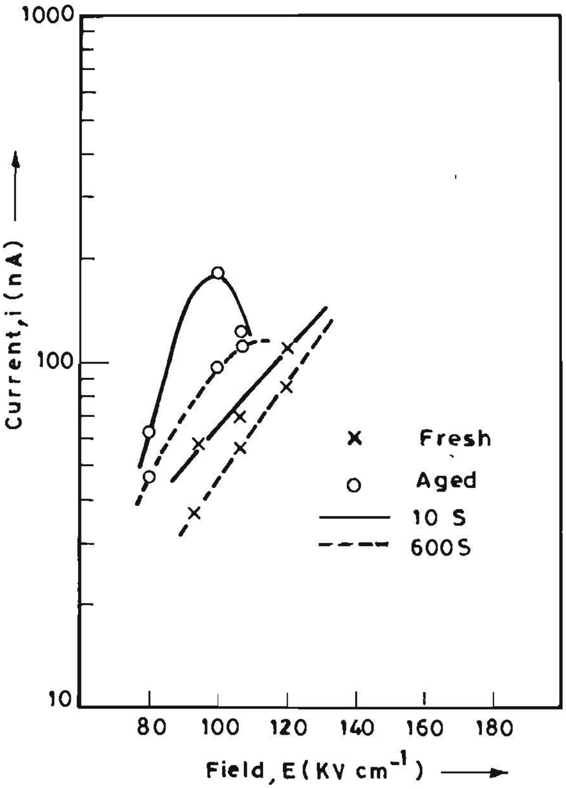

Fig. 8: **Field Dependence of Conduction Current at 10 s and 600 s, Using 5–15 μm Filter and Nickel Anode.**

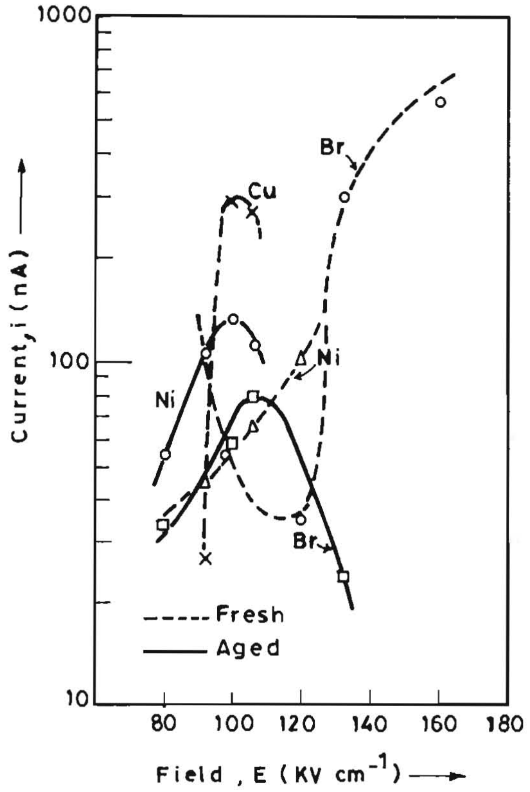

Fig. 9: Effect of Anode Material on the *i–E* Characteristic at 100 s, Using 5–15 μm Filter.

role played by the anode material in modifying the *i–E* characteristic in this study leads to explain the nature of anode/liquid interface reactions which result in a surface layer consisting of an insulating film and space charge effecting the conduction in opposition. The insulating film decreases conduction because it is more difficult for the ions to be neutralized on the anode, whereas the space charge enhances the local field at the anode and hence carrier collection.

This insulating film may be formed owing to the polymerization and oxidation process in aged oil, the reaction being stronger in aged oil because of its high acidity [12] which forms a more stable layer. As the field increases, this film decreases the conduction, but when the field is increased further this film is ruptured and the conduction increases steeply. The value of the critical field at which the current starts to decrease is higher in the aged oil than in the fresh one. The difference may be due to different dielectric constants of the layer in both oils.

Conclusion

From this experimental study, the following conclusion can be drawn at this stage:

1) The conduction current decays exponentially with the increase of time.

2) Although dehydration and filtration partially remove impurities and moisture from aged oil, it still makes the oil more homogenized which may result in an increase of conduction current.

3) The anode material and anode/liquid interface play important roles in conduction phenomena.

4) For a specific field range, the *i–E* characteristics exhibit a phenomenon which resembles tunnelling effect occurring in semi-conductors.

5) Although this paper sheds some light on the interactions at the metal/liquid interface, there is still a need for further investigations.

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References

1. **Forster, E.O.,** Electrical Breakdown in Liquid hydrocarbons, *Proc. 7'ICDL, Berlin, West Germany,* pp. 105–109 (1981).
2. **Barnes, F.S.,** A Review of the US–Japan Seminar on Electrical Conduction and Breakdown in Dielectrics and Some Thoughts on Problems to be Solved, *IEEE Trans. on Elect. Ins.,* Vol. **EI–15,** No. 3, pp. 131–133 (1980).
3. **Sharbaugh, A.H., Devins, J.S.,** and **Rzad, S.J.,** Progress in the field of Electric Breakdown in Dielectric Liquids, *IEEE Trans. on Elect. Ins.,* Vol. **EI-13,** No. 4, pp. 249–276 (1978).
4. **Adamczewski, I.,** *Ionization, Conductivity and Breakdown in Dielectric Liquids,* Taylor & Francis Ltd., London, 1969.
5. **Brignell, J.E.,** Complexities in the High Field Behaviour of Moderately Pure Liquids, *Proc. 7'ICDL, Berlin, West Germany,* pp. 105–109 (1981).
6. **Felici, N.J.,** A Tentative Explanation of the Voltage Current Characteristic of Dielectric Liquids, *Proc. 7'ICDL, Berlin, West Germany,* pp. 110–114 (1981).
7. **Shimokawa, H., Ohashi, A.,** and **Ueda, M.,** Conduction Current in Silicone Liquid Films, *J. Electrostat,* **7,** pp. 187–197 (1979).
8. **El-Sulaiman, A.A., Ahmed, A.S.,** and **Qureshi, M. Iqbal,** Quasi Steady and Burst Current in Aged Transformer Oil under High Direct Field, *IEEE Trans. on Elec. Ins.,* Vol. **EI-16,** No. 5, pp. 453–457 (1981).

9. **Nakagami, Y.** and **Okamoto, T.**, Experiment on the Increase of Impurities in Transformer Oil by Electrical Discharge, *14th Symp. on Elec. Ins. Materials, IEE (Japan) Tokyo*, Japan, Oct. 5–7 (1981).

10. **Inuishi, Y.**, High Field Conduction and Breakdown in Dielectric Liquids, *J. Electrostat*, **7**, pp. 1–11 (1979).

11. **Egger, H., Horak, W., Praxl, G.** and **Zwichangl, W.**, On the Operating Behaviour of Insulating Oils in High Voltage Transformers, *Proc. 7'ICDL, Berlin, West Germany*, pp. 460–464 (1981).

12. **El-Sulaiman, A.A., Ahmed, A.S., Qureshi, M. Iqbal** and **Hassan, M.M.A.**, High Field DC Conduction Current and Spectroscopy of Aged Transformer Oil, *IEEE Trans. on Power Apparatus and Systems*, Vol. **PAS-101**, No. 11, pp. 4358–4360, Nov. (1982).

13. **Kao, C.** and **Calderwood, J.H.**, Effects of Hydrostatic Pressure, Temperature, and Impurity on Electric Conduction in Liquid Dielectrics, *Proc. IEE*, Vol. **112**, No. 3, pp. 597–601 (1965).

دراسة تيار التوصيل المستمر للزيوت المستعملة في المحولات تحت تأثير المجال العالي الغير متماثل

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المملكة العربية السعودية .

تركز هذه المقالة على النتائج التجريبية لتيار التوصيل المستمر في زيوت محولات الضغط العالي المستعمل تحت تأثير مجال غير متماثل .

تمت دراسة ومناقشة تأثير استخلاص الرطوبة والترشيح من الزيوت ونوع مادة مصعد الخلية وشدة المجال الكهربائي .

استنتج البحث أن العلاقة بين التيار والزمن يمكن تمثيلها بدالة لوغارتيمية ولوحظت ظاهرة « النفقية » في العلاقة بين التيار والمجال الكهربائي .

علاوة على ذلك فان عملية تحضير العينات ومنطقة ملامسة المصعد مع الزيت تلعب دورا هاما في ميكانيكية التوصيل المستمر تحت تأثير المجال الكهربائي غير المتماثل .

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