Comparative study of the degradation rate of new and regenerated mineral oils following electrical stress

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Abstract : The objective of this contribution was to study the behaviour of new and regenerated insulating oil used in power transformers under the influence of an electric stress. To estimate the degradation rate of the dielectric fluids, one thousand (1000) successive breakdowns were generated according to the IEC 60156 standard. The parameters such as dissipation factor (Tan δ), resistivity, total acid number (TAN) and oil water Content were measured and examined following IEC/ISO standards. Good correlations have been obtained between TAN/resistivity and Tan δ which might provide a "picture" of the fluid condition. The dissolved oxidation products for the two dielectric fluids (after the application of electric breakdowns), was evaluated by infrared spectroscopy (FT-IR). The results obtained indicate that the degradation of the parameters is significant and confirms the influence of an alternative electric field (AC) on the new and regenerated oils. It was also suspected that inhibitors and antioxidants were removed from the oil after regeneration. Their concentration should therefore be monitored and replenished when necessary.

1. Introduction

Power Transformers are one of the vital and expensive elements in the industry of electrical energy. Their essential functions in the transmission and distribution allows them attracting attention of engineers and researchers. Especially, their insulation mainly composed of mixed cellulosic materials and oil, are of concerns. Their condition and life span can be mathematically or experimentally evaluated by the physicochemical, electrical or mechanical characteristics of their insulation system **[1] [2]**. A large number of power transformers are filled with mineral oils because of their advantages that constitute unique combinations of dielectric, cooling and oxidation stability properties **[3].**

Power transformer oil undergoes continuous deterioration and degradation because of electrical, thermal, mechanical, and environmental stresses occurring during operation **[4]**. Therefore any deterioration in the oil can lead to premature failure of the equipment. When the mineral oil is subjected to high thermal and electrical stresses, gases are generated from the decomposition of the molecules **[3]**.

The electric stress accelerates ageing, possibly by increasing the precipitation of acid produced from the oil degradation onto paper surfaces. Chemically speaking, the acid build-up will worsen the insulating paper tensile strength.

Aggressive decay products being absorbed by the solid insulation attack the cellulose fibres too. Sludge produced may stick onto the large surface of power transformer, and affects heat transfer between the core/coil and the tank/radiators surfaces.

The cracking process of cellulose (depolymerisation by a succession of chemical reactions) causes chain scissions along with release of gases and moisture into the surrounding oil and some large molecules such as furfurals. In the complex oil-impregnated dielectrics used in high voltage insulation, oil is usually the weaker component of the system, both in dielectric strength and in reaction to environmental stress. Knowledge of the stability of insulating oils under electrical stress is of upmost importance to both electrical-equipment designers and operating engineers.

The process of decomposition of insulating oils under electric stress begins with the breakdown of unstable mineral oil molecules covalent bonds. Oxygen, moisture or other chemical reactive radicals can spontaneously be generated; the process being catalysed by heat **[5] [6]**. Free radicals are very reactive and can adversely affect the physicochemical and dielectric properties of the insulating oil. The sources of energy at the origin of a covalent bond splitting are three folds:

- The strong electro-magnetic stress at the origin of the free electron injection process in the insulating fluid**[7]** [8].
- The thermal stress generated by the active parts.
- And finally, the aggressiveness of dissolved oxygen.

Free electrons (e-) accelerated by electric field, are primary source for the breakdown of vulnerable covalent bonds (approximately 4 eV ≈ 386 kJ mol^{-1}). Electrons escape from the conduction band of the metal conductor and are emitted from its surface, especially during very short but frequent voltage surges **[9] [10]**.

2. Motivation for the work

The goal of this study is to study the behaviour of new and regenerated mineral oils under the impact of an electric stress. For this purpose, the degradation rate of some physicochemical and the electric properties of the insulating oils were assessed. All the obtained results are compared and analysed.

Table 1 Insulating fluid properties before electrical stress applications.

Test	Standard	Unit	New Oil	Regenerated Oil
			Value	
Total Acid Number (TAN)	IEC 62021	mg $_{KOH}$/g	0.009	0.026
Water Content	IEC 60814	p.p.m	19.6	18.6
Dissipation Factor at @50 Hz, 90 °C	IEC 60247	—	0.0014	0.0027
Permittivity (90 °C), ε_r	IEC 60247	—	2.12	2.12
Resistivity (90 °C) x 10^9	IEC 60247	Ω.m	250.13	484.29
Dielectric Breakdown Voltage	IEC 60156	Kv	60	58
Kinematic Viscosity at 40 °C	ISO 3104	mm^2/s	6.558	6.777
Density	ISO 3675	g/ml	0.830	0.84
Color Factor	ISO 2049	—	< 0.5	1.6

3. Sample description

3.1 New oil

Power oil, a naphthenic, uninhibited, mineral oil produced by APAR INDUSTRIES LTD was considered. This high grade is referenced as new oil. Power oil serves as comparison baseline for the regenerated oil in the following benchmark tests.

3.2 Regenerated oil

The present study proposes a regenerated oil sample, recovered by a process of regeneration based on the principle of a physical and chemical treatment. The proposed protocol of regeneration was already verified **[11]** by coupling the centrifugation, the dehydration and the sorption with four different adsorbents: activated carbon (ACH), silica gel (SG), oxide of magnesium (MO) and the activated bentonite (AB). The method of regeneration optimized in this study ended in a level of restoration of the properties close to the new oil.

3.3 Properties of transformer oils

The new and regenerated oils are referenced as fluids of base 1 and 2 respectively. Their initial properties are listed in **Table 1**.

3.4 Materials and methods

The physical, chemical and electrical properties have been assessed according to the standard specifications given by the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO). The properties of the oil samples were assessed using the following equipment:

- BAUR DTLC Dielectric Strength Tester (Germany), used for measuring the dielectric dissipation factor according to IEC 60247 **[12]**.
- Burette Digital TITRETTE-BRAND, used to determine the acidity index according to IEC 62021.

  The acid number indicates the number of mg potassium hydroxide (KOH) needed to neutralize each g of oil sample. The end point of titration was determined using phenolptaline indicator **[13]**.
- METROHM 756 KF COULOMETER (Switzerland), used to determine the water content in ppm according to IEC Standard 60 814. The measurement is repeated three times to assess repeatability. The final water content is the average of the three water contents **[14]**.
- Density is measured according to ISO Standard 3675 standard (limit value <0.91) by using a test-tube, a densimeter and a thermometer **[15]**.
- MEGGER OTS 100AF/2 (USA), used for determining the Dielectric Breakdown Voltage according to IEC Standard 60156 with a testing voltage up to 100 kV. The breakdown voltage was measured using a bispherical standard cell with 2.5 mm spacing in dielectric liquid. An AC voltage with frequency of 50 Hz was applied with an increasing rate of 2 kV /s **[16]**.
- LOVIBOND PFX 195 Spectrophotometric Colorimeters Tester (UK), used for measuring the oil color according to ISO 2049 **[17]**.
- LABOVISCO TAMSON TV 2000 (Holland), used to determine the kinematic viscosity according to ISO Standard 3104. The method is based on the bbelohde principle. The speed flow of the oil in a vertical capillary under atmospheric pressure is converted to the kinematic viscosity **[18]**.
- FT-IR spectrums were recorded with a VERTEX BRUKER Spectrometer. Spectroscopy is based on the principle that the molecules in a lubricant can absorb infrared light at corresponding wavelengths depending on its typical structure. Changes in the used sample in comparison to the fresh reference oil spectrum are calculated on the typical peaks at predefined wave numbers. The sample is pumped into a flow cell.

  The space between two thin zincselenide (ZnSe) glass plates with a distance of 0.1 mm must be completely filled. Infrared light over the complete range of the infrared light spectra is sent through the cell. The detection takes place on the other side at a receiver module. As some parts of the infrared light are absorbed, the detector signal is different from the source signal. According to the principle of Fourier transformation, the signal is calculated into the typical FTIR diagram.

4. Experimental procedure

4.1 Electrical Ageing procedure

The accelerated electric ageing in laboratory was performed by successive and continuous application of one thousand (1000) breakdown discharges on the new and regenerated oil samples. The breakdown test was performed according to the IEC 60156 standard **[13]**.

This test method implies that a constant incremental voltage of 2 kV /s was applied to the test cell containing the oil sample until the breakdown occurred (**Fig.1)**.

Fig.1. *Megger OTS 100 AF/2 installation for breakdown testing the mineral:* (a) general view, (b) testing oil tank.

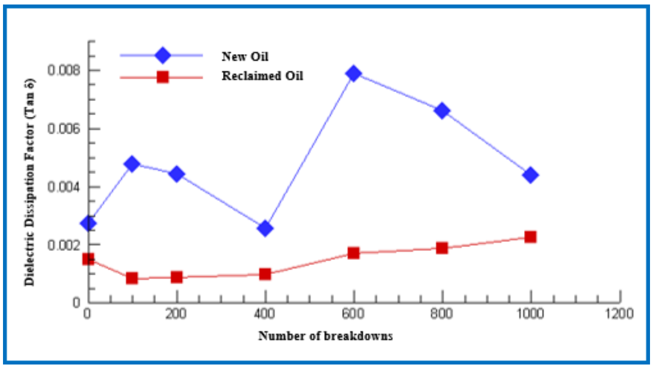

Fig.2. *Tan δ as function of number of breakdown.*

4.2 Ageing Rate

Various physicochemical and electric properties were measured to detect changes and determine the rates of ageing of the fluids **[19]**: Dissipation Factor (Tan δ), Resistivity, Total acid number (TAN) and Water Content in both new and regenerated insulating fluids. The ageing rates were assessed according to the equations (1)-(4). The reference values were obtained with initial new and regenerated oils samples. Those fluids are referenced as "news", whereas those obtained at the end of electrical ageing are referenced as "aged".

$$\Delta \frac{Tan\,\delta_D}{Tan\,\delta_{new}} = \frac{(Tan\,\delta_{aged} - Tan\,\delta_{new})}{Tan\,\delta_{new}} \times 100 \quad \textbf{(1)}$$

$$\Delta \frac{Resistivity_D}{Resistivity_{new}} = \frac{(Resistivity_{aged} - Resistivity_{new})}{Resistivity_{new}} \times 100 \quad \textbf{(2)}$$

$$\Delta \frac{TAN_D}{TAN_{new}} = \frac{(TAN_{aged} - TAN_{new})}{TAN_{new}} \times 100 \quad \textbf{(3)}$$

$$\Delta \frac{Water\ Content_D}{Water\ Content_{new}} = \frac{(Water\ Content_{aged} - Water\ Content_{new})}{Water\ Content_{new}} \times 100 \quad \textbf{(4)}$$

5. Results and discussions

The oxidation of the oil is a complex process that involves free radicals in chains reactions **[20]**. Free radicals are electrically charged particles which require electrons from other molecules to achieve stabilization. They have one or more unpaired electrons which make them chemically very active to react with other molecules. Among the other properties of these free radicals are their para-magnetism nature caused by unpaired electrons, electric neutrality, as well as their tendency to concentrate in a strong electric field. Due to the concentration under electric fields, the free radicals recombine to produce more decay compounds **[7]**.

The oxidation process of hydrocarbons involves three basic stages: initiation, propagation and termination. In the initiation stage, oxygen reacts spontaneously to breakdown a hydrogen molecule and form hydro-peroxides, which again dissociate into free radicals. The propagation is a rapid progression of the branched chains reactions, and the termination occurs with the formation of stable intermediate radicals and nonreactive compounds that donate hydrogen molecules to the free radicals **[21]**. The breakdown of power transformer oil due to electrical stress has been explained by the theory of avalanche ionization of atoms dissociated by electron collisions **[22]**.

During discharge events, electrons are generated in the oil from the cathode, creating an electro-thermal condition that produces localized high temperatures. In this condition, small gas bubbles are generated as charge carriers which propagate further due to the oil ionization, that in turn cause further generation of fault gases.

The samples were stressed electrically under AC voltage. Determining Dielectric dissipation factor (Tan δ), Resistivity, water content and the Total Acid Number (TAN) of the fluid samples after electrical ageing tests and comparing them with those obtained before (**Table 2**).

5.1. Dielectric dissipation factor (Tan δ)

The dielectric dissipation factor measures the dielectric losses in the oil and it is very sensitive to the presence of soluble polar contaminants, ageing products or colloids in the oil **[21].** When insulating fluid is subjected to an alternating current (AC) current, there are dielectric losses, which cause two effects. The resulting current is deflected slightly out of the phase with the AC field that has been applied, and the energy of the losses is dissipated as heat.

Table 2 Insulating fluid samples assessment after electrical stress.

OXYDATION OIL (Number of breakdowns IEC 60156)												
	Dissipation factor (tan δ)			**Resistivity (E+09Ωm)**			**Water content (ppm)**			**TAN (mg_{KOH}/gr)**		
	0	1000	$\Delta \frac{Tan\,\delta_D}{Tan\,\delta_{new}}$	0	1000	$\Delta \frac{Resistivity_D}{Resistivity_{new}}$	0	1000	$\Delta \frac{Water\ Content_D}{Water\ Content_{new}}$	0	1000	$\Delta \frac{TAN_D}{TAN_{new}}$
New Oil	0.0014	0.0022	**57.14**	250.13	45.45	**81.77**	19.6	12.2	**- 38**	0.009	0.032	**255.55**
Regenerated Oil	0.0027	0.0044	**62.96**	484.29	189.78	**60.81**	18.6	27.5	**48**	0.026	0.088	**238.46**

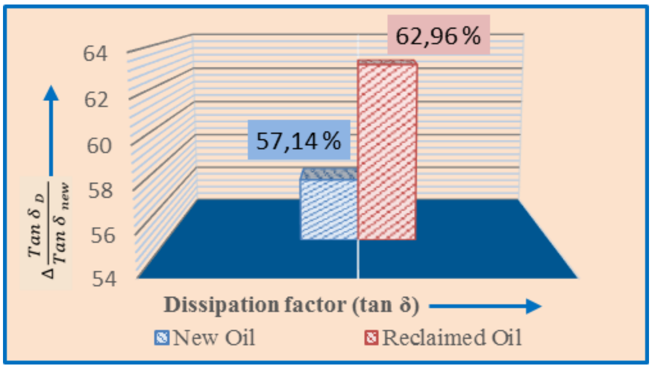

***Fig.3.** Rate of ageing of the parameter Tan δ after electric stress.*

Liquid power factor and the closely related dissipation factor are direct measures of these dielectric losses. Contamination by moisture or by many other contaminants will increase the dissipation factor. The ageing and the oil oxidation also increase the values **[22]**. The dielectric loss factor can be used to monitor the quality of this oil, with regard to in-service deterioration and for the presence of contaminants **[23].** With an increase in the population of free radicals, their unpaired electron can be coupled with a free electron to become charge carrier that tends to increase in turn the dissipation factor of the fluid **[24]**.

Fig.2 and **Fig.3** show that the variations of the rate of increase of Tan δ are important for the new and regenerated oil samples. The ageing rate is equal to 50% for the new oil and 60% for the regenerated oil. We also notice that the Tan δ of the regenerated oil worsens considerably and more quickly than the new dielectric fluid under the same ageing conditions.

5.2. Dielectric Resistivity

Resistivity or specific resistance is the most sensitive property of the oil; it varies with temperature, moisture, contaminants and charge carriers. It is desirable to have the highest resistivity of oil as possible. The resistivity of oil reduces considerably due to the presence of moisture, acidity, solid contaminants, etc. High resistivity reflects low content of free charge carriers and ion-forming particles and indicates a low concentration of conductive contaminants **[23]**.

The variation of the dielectric resistivity when the insulating fluid is subjected to an electric breakdown is shown in **Fig.4** and **Fig.5**.

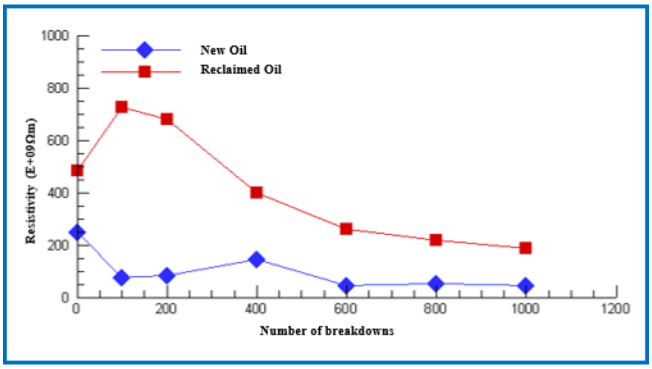

***Fig.4.** Dielectric Resistivity as function of number of breakdown.*

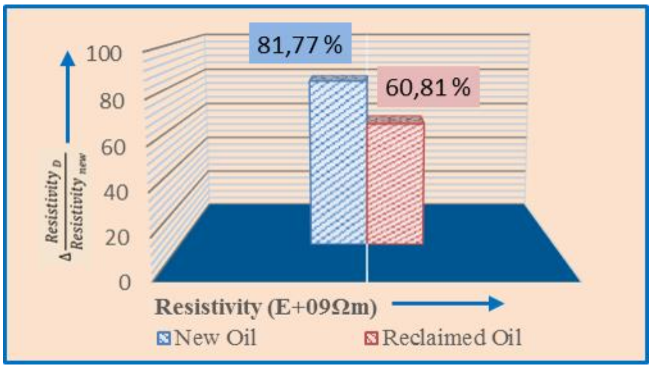

***Fig.5.** Rate of ageing of the parameter dielectric resistivity after electric stress.*

It can be observed that the dielectric resistivity decreases for the new and regenerated oils and represent ageing rates equal to 81.77% and 60.81%, respectively.

5.3. Total Acid Number (TAN)

Even though there are different types of wear on a insulating oil, the main force of ageing is of course oxidation. For oxidation to take place, it is necessary that something oxidize (oil), oxygen and heat can provide the activation energy.

When a hydrocarbon molecule (oil molecule) encounters the combination of heat and oxygen (air), it can form a peroxide (**Fig.6**).

Peroxides are inherently unstable and therefore rather reactive. They can easily form alcohols or aldehydes or ketones. These are polar types of molecules that will change the properties of the oil medium in which all this happens. Aldehydes and ketones can react again with oxygen to form acids directly, or be oxidized and loose carbon dioxide to form acids.

Carbon dioxide is in fact the most oxidized form of carbon and the absolute end of the process.

However, both aldehydes and acids can react with each other to form complex compounds **[24]**.

Out of **Fig.7** and **Fig.8**, it can be observed that the rate of increase of TAN is significant for the new and regenerated oil samples and represents an ageing rate of 256% for the new oil against 238% for the regenerated oil, which confirms the formation of the acids.

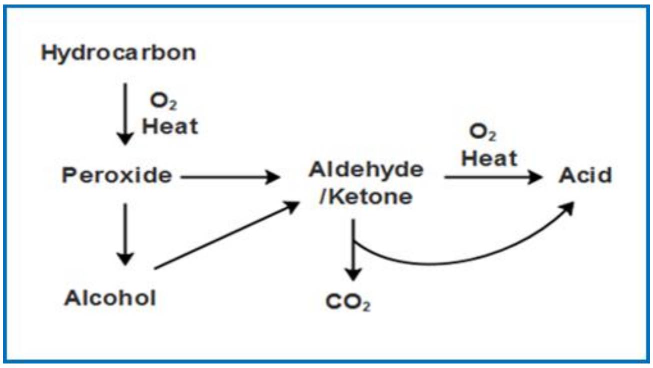

***Fig.6.** Principle of transformer oil oxidation **[24]**.*

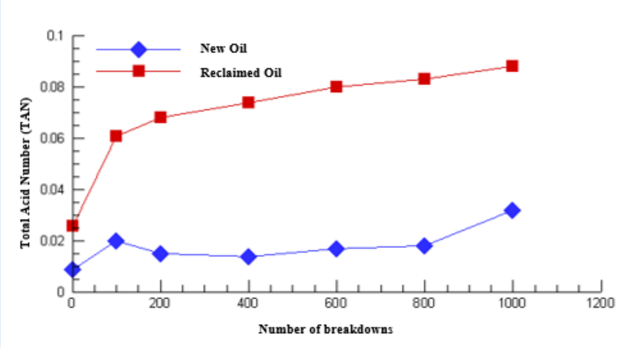

Fig.7. *TAN as a function of breakdown number.*

Many investigations **[4, 25-27]** have shown that the dissolved decay product analyzed by infrared spectroscopy (FT-IR), can be used as a parameter to indicate the insulating oil degradation.

This sensitivity to the molecular oil components can be used to trace the ageing by-products. The infrared (IR) spectra for the new and regenerated oils are shown in **Fig.9**.

Electrical stress stemming from the reactions with the molecules of oxygen and the insulating liquid, results in the degradation of the insulating oil properties.

This mechanism is amplified largely by increasing temperature. An increase in the temperature of 10°C leads to approximately a doubling of the oxidation rate **[27]**.

As the insulating oil ages, the acid and peroxide contents increase, forming C = O bonds during oxidation and C=C double bonds during thermal decomposition **[28]**. According to reference **[29]**.

Table 3 represents the functional groups of the new and regenerated oils samples shown in **Fig.9**. The strong frequencies of absorbance at 2924.34 cm^{-1} and 2854.5 cm^{-1} represent C-H stretching. The regions of frequency between 2800 and 3100 cm^{-1} represents the vibrations of C-H bonds, an intensive band and widened for hydroxyls bands–OH of an acid at 3442.79 cm^{-1}**[30]**. Fingerprints of the aromatic compounds are detected in the range 1450-1600 cm^{-1}. A little intense band also appears towards 800 cm^{-1} which confirms the unimportant presence concerning the functional bands groups (C = O (carbonyl), **-** N (amino) and **-** OH (hydroxy) in the composition of the oil **[3]** and those of strain attributed to the bands of the C=O group, between

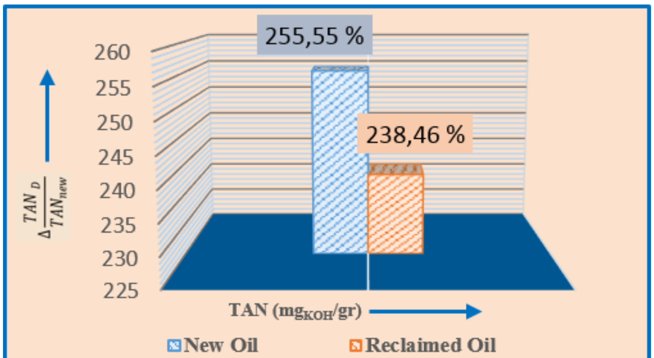

Fig.8. *Rate of ageing of the parameter TAN after electric stress.*

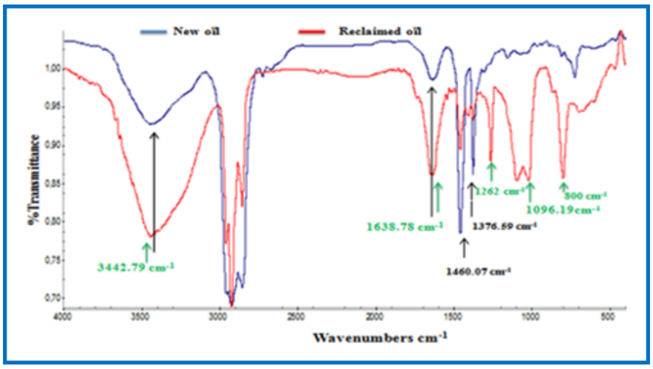

Fig.9. *FT–IR spectra of the new and regenerated oils after electric stress.*

1600 and 1820 cm^{-1} **[23]** and a nitro grouping C-NO_2 in the region 1376.59 cm^{-1}. In the spectral regions between 1050 and 1300 cm^{-1} it is supposed that with the progress of oxidation of the regenerated oil sample, diverse oxidation products are formed and which can be the ester.

The apparition of three characteristic bonds of ester function formation (C-O) happens at approximately 1021.86 cm^{-1}, 1096.19 and 1262.18 cm^{-1}.

5.4. Water Content

Moisture content either comes from the atmosphere or is due to the deterioration of insulating materials **[31]**. Moisture remains in oil with low volume and can be measured by chemical or electrical methods. The increase of temperature and neutralization level will increase the saturation level of oil.

As a result, free water will be produced, which in turn will decrease the electrical strength and resistivity of transformer insulation system **[32]**.

As water molecules have high dipole moments, they will become polarized in electrical field and turn to increase the dielectric dissipation factor **[33]**.

Fig.10 and **Fig.11** show the variation of the water for the new and regenerated oils as function of the electric stresses. For comparison purposes, it can be noticed that the rate of water is considerably higher for the regenerated oil (48%) against an appreciate decrease of the moisture content of the new oil (38%).

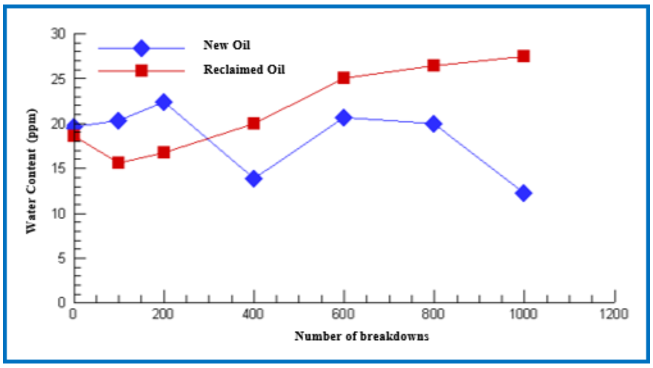

Fig.10. *Water Content as function of breakdown number.*

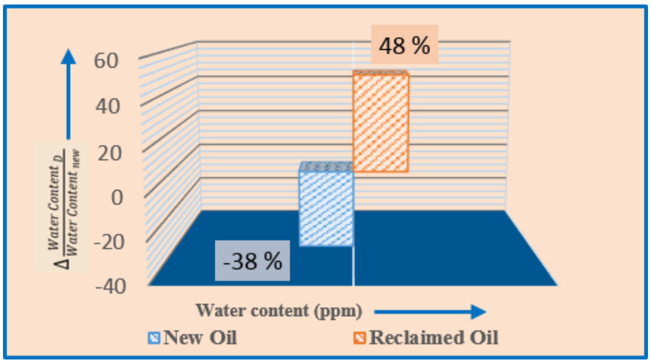

__Fig.11.__ Rate of ageing of the parameter water content after electric stress.

These results confirm that oil with an important content in naphthenic molecules (which is the case of the new oil) presents excellent properties and a big solvability for the oxidation of the products and the moisture **[30].**

Table 4 presents a simplified general model of possible reactions which occur during the oxidation of transformer oils **[34]**.

Reactions (5), (6) and (7) correspond to the initiation stage, in which peroxides and free radicals are produced under the influence of heat, high electrical stress and metal catalysts.

From reactions (8) the propagation and branching take place, resulting in the production of some stable and soluble by products, such as alcohols, aldehydes, carboxilic acids, ketones, ester and water **[35]**.

Table 3 Identification of the functional groups in the composition of new and regenerated oils samples after electric ageing by infrared spectroscopy (FT-IR) analysis.

New Oil			Regenerated Oil		
Frequency (cm^{-1})	Absorbance	Bond types	Frequency (cm^{-1})	Absorbance	Bond types
1376.59	2.03	$C\text{-}NO_2$	800.09	2.07	C = O, -N et -OH
1460.07	2.06	Aromatic contents	1021.86	2.07	Ester
1640	1.99	$- COO^-$	1096.19	2.07	Ester
3445.89	2.01	- OH	1262.18	2.07	Ester
2854.5	2.08	C-H stretching	1459.40	2.06	Aromatic contents
2924.34	2.16	C-H stretching	1639.67	2.06	$- COO^-$
			2854.5	2.08	C-H stretching
			2924.34	2.16	C-H stretching
			3442.79	2.13	- OH

Table 4 Degradation mechanism of transformer oil by redox reactions: R and R' are organic radicals with identical or different hydrocarbons.

RH	$\rightarrow R^{\cdot} + H^{\cdot}$	(1) Formation of free radicals
$R^{\cdot} + O_2$	$\rightarrow RO_2^{\cdot}$	(2) Formation of peroxy-radical
$RO_2^{\cdot} + RH$	$\rightarrow RO_2H + R^{\cdot}$	(3) Formation of Peroxide
ROOH	$\rightarrow RO^{\cdot} + OH^{\cdot}$	(4) Decomposition of peroxide
$R^{\cdot} + R^{\cdot}$	$\rightarrow R - R$	(5) Generation of hydrocarbon
$RO^{\cdot} + RH$	$\rightarrow ROH + R^{\cdot}$	(6) Alcohol + Radical formation
$OH^{\cdot} + RH$	$\rightarrow H_2O + R^{\cdot}$	(7) Water + Radical formation
$2ROH + O_2$	$\rightarrow 2RCHO + H_2O$	(8) Aldehyde formation
$2ROH + O_2$	$\rightarrow 2RCHO + H_2O$	(9) Ketone Formation
$2RCOH + O_2$	$\rightarrow 2RCOOH$	(10) Carboxylic acid formation
$2RCOOH + ROH$	$\rightarrow 2RCOOR + H_2O$	(11) Ester formation

The hydrocarbon molecules follow the reaction path and lead to the accumulation of the byproducts until the action of certain inhibitors form termination products suppressing further oxidation. Antioxidants are compounds that resist to the oxidation process.

The antioxidant performs electron scavenging mechanism by trapping free radicals or free electrons present in the solution, thus completely purging the chain reaction. The amount of free radicals is kept to minimum quantity; it can slow down the oil oxidation and peroxide formation **[36]**.

Actually, oxidation process inside oil is controlled or slowed down by preventive maintenance procedures by incorporating oxidation inhibitors or antioxidants with the aim of interrupting and terminating the free radical process of oxidation.

The main functional mechanisms of antioxidant are free electron scavenging, metal chelation and synergism **[37, 38]**.

The inhibitor content should be monitored and replenished when needed.

Reclamation processes carried using activated carbon and clay treatment can remove contaminants like sludges, metals and acids. But this could likely decrease the amount of natural oxidation inhibitors present in the oil **[36]**.

The performances of antioxidant under normal and higher temperature conditions vary. They are consumed in service. Inhibitors used in transformer oils offer stability for a limited time. The so-called the induction period' after which the oil oxidizes at the normal uninhibited rate **[39].**

The impact of the degradation of the parameters TAN and Dielectric loss factor (Tan δ) as well as dielectric resistivity must be estimated.

Correlations between the properties of oil (TAN, Tan δ and Resistivity) are respectively summarized in **Fig.12** and **Fig.13**.

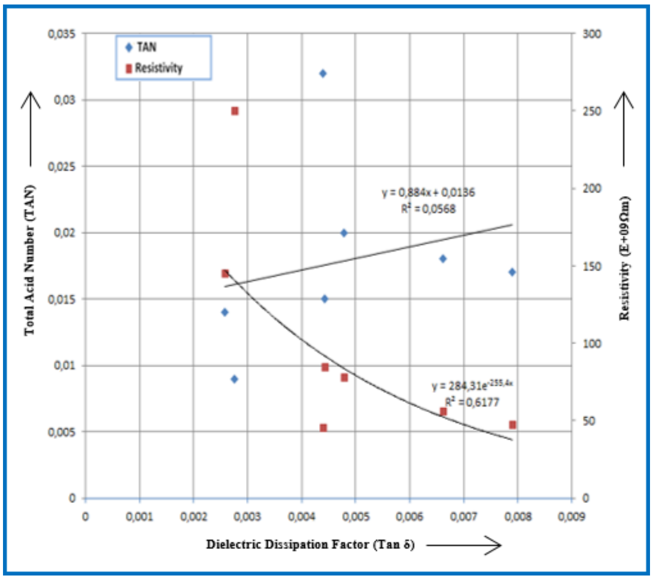

Fig.12. *Correlation between the Dielectric Dissipation Factor (Tan δ), Total Acid Number (TAN) and Resistivity of New oil after electrical stress.*

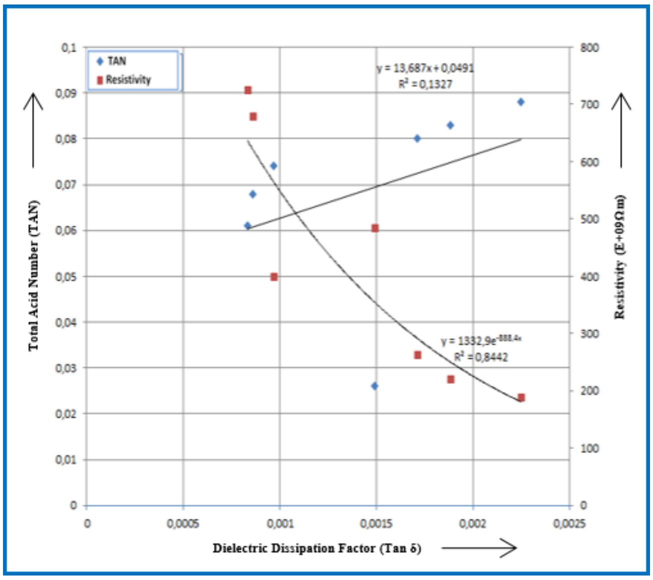

Fig.13. *Correlation between the Dielectric Dissipation Factor (Tan δ), Total Acid Number (TAN) and Resistivity of Regenerated oil after electrical stress.*

A mathematical approach to process the data of electric ageing reveals an identical variation for the two new and regenerated oils samples. The TAN carries a linear relation with the parameter Tan δ, whereas an exponential relation between the parameter dielectric Resistivity and Tan δ exists.

The relation between the TAN and the Tan δ can be fitted by a linear function type **Equation (5)**.

$$\mathbf{TAN = A + B(Tan\delta)} \qquad \textbf{(5)}$$

Where A = Initial value of acidity (mg $_{KOH}$/g)
B = Constant (mg $_{KOH}$/g)

Based on the analysis of the function, it was noticed that the acidity (TAN) shows one clear incremental pattern with Dielectric loss factor (Tan δ). This can be a good representative candidate of ageing indicator of the dielectric fluids (new and regenerated).

Equation (5) was considered appropriate to represent the relation between TAN and Tan δ of the dielectric under the impact of an electric stress, where A represents the value of the initial acidity of each oil sample.

The parameters were adjusted according to values reported in **Table 5**.

Table 5 adjustment of parameters used in equation (5).

Fitting parameter	New oil	Regenerated oil
A	0.0136	0.0491
B	0.884	13.687
R^2	0.0568	0.1327

And with the analysis of the trends, it was noticed that the variation of parameter resistivity according to dielectric loss factor (Tan δ) can be interpolated by an exponential function (**Equation 6**) with two stages. The first stage represents a slow ageing while the second stage defined a fast ageing rate.

The first stage is controlled by the constant B, while the second stage is controlled by the rate of decrease of the dielectric resistivity C.

$$\mathbf{Resistivity = A \cdot e^{(B \cdot Tan\delta)}} \qquad \textbf{(6)}$$

Where A = Constant (Ω.m)
B = Rate of resistivity

The parameters were adjusted according to values reported in **Table 6**.

Table 6 adjustment of parameters used in equation (6).

Fitting parameter	New oil	Regenerated oil
A	284.31	1332.9
B	-255.4	-888.4
R^2	0.6177	0.8442

6. Conclusion

The aim of this study was to assess the rate of ageing and oxidation of new and regenerated oils used in power transformer under electric stresses. Some important ageing indicators such as loss Factor (Tan δ), Total Acid number (TAN), dielectric resistivity and Water Content were used to monitor the degradation rate. From the obtained results, the following differences were observed:

- A rate of significant variation of the parameter Tan δ which represents 50% for the new oil and 60% for the regenerated oil confirming the ageing and the oxidation of the oil.
- The dielectric resistivity decreases for the new and regenerated oils and represent respectively an ageing rate of 81.77% and 60.81%.

- Distinctive increase of the TAN which represents an ageing rate of 256% for the new oil against 238% for the regenerated oil and which confirms the formation of acids.
- A rate of evolution of the moisture content of 48% for the regenerated oil against a rate of reduction of 38% for the new oil.
- Good correlations have been obtained between TAN/resistivity and Tan δ which might provide a "picture" of the fluid condition. These correlations should be considered in the frame work of the experimental conditions.

The generation of ageing by-products was confirmed by (FT-IR) infrared spectroscopy after electric stress applied to regenerated oils. It was suspected that inhibitors and antioxidants were removed from the oil after reclamation. Their concentration should therefore be monitored and replenished when necessary.

7. References

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