

EFFECTS OF THE CONSTITUENTS OF TRANSFORMER WINDING DEPOSITS ON THE BREAKDOWN VOLTAGE OF TRANSFORMER OIL

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ABSTRACT

In this study the infrared analysis of different transformer oils and transformer winding deposits in order to investigate their constitutions has been carried out. The analysis showed that the deposits have the same constituents of the transformer oil in addition to some other compounds and acids which might be formed due to aging effects. The acidity of deposits is higher than those of the transformer oil. The metallic content of the deposits has been found by atomic absorption spectroscopy analysis of deposits. The studied deposits have showed that they have either iron or copper particles. The effect of using these deposits as contaminants on the breakdown voltages of new and aged (used) oils has been investigated. It has been found that the transformer oil breakdown voltages decrease with the increase in the amount of deposits. Transformer oils with copper deposits have lower breakdown voltage than those with iron deposits. This is due to the difference in conductivities. The breakdown voltage of aged oil is less sensitive to deposit contaminants than the new oil.

Keywords: Transformer winding deposits, Infrared analysis, Atomic absorption spectroscopy, Breakdown voltage.

1. INTRODUCTION

Aging of transformer oils results from several factors which are encountered during the continuous operation of transformers. These factors include variation of thermal and electric stresses, generation and dissociation of acids. Most researchers studied the aging of the transformer oil by investigating the physical, chemical and electrical characteristics of transformer oil samples [1]. However, the aging of transformer oil in the presence of insulated conductors may yield other products which can not be sustained in the transformer oil for long periods. These products may be deposited over the surfaces of transformer conductors, core and the container by the electrical and thermal stresses [2]. One of the objectives of this study is to understand the conditions that the transformer has been subjected to by the analysis of the constitution of the material of the deposits. Therefore infrared analysis of these deposits for different transformers and analysis of

used and purified aged transformer oils have been carried out. Infrared spectroscopy has been used extensively in polymer degradation research as a tool for examining structure changes and identifying the functional groups present [3]. The past decade has seen great progress in the understanding of the mechanism involved in the electrical breakdown of insulating liquids, but the factors such as particle contamination are still the prime concern [4]. Conducting particles have adverse effects on the dielectric strength of liquids [5]. However, most of the work has been devoted to show the deleterious influence of large amounts of small particles on the dielectric strength of the transformer oil [6]. Studying the effects of conducting particles on the breakdown voltage of the transformer oil by using artificial metallic contaminant particles with certain shape and material will not give accurate results. This is due to the fact that the particles which may

be formed inside the transformer oil do not have specific shape and may have some chemically treated coating layers. The shape of the actual contaminant particles and coating layers will be affected by the chemical compounds present in the transformer oil specially water, acids, wax and other products and also by the continuous thermal stress. Therefore it is required to have some metallic particles subjected to the actual aging or treatment as those created inside the transformer oil during operation. The purpose of this part of the study is to override the previously mentioned drawback in the study on the effects of metallic particle contamination on the Breakdown Voltage (BDV) of transformer oil. The investigated deposits have been used as contaminants. The amount of deposit contaminant has been varied with very small ratios. The effects of the type and quantity of the deposit contaminants on the BDV of the transformer oils have been investigated.

2. EXPERIMENTAL METHODS

2.1 Transformer oil and deposit samples

This experimental study was carried out using four transformer oil samples designated as "A", "B", "E" and new transformer oil and two samples of deposits designated as "C" and "D". All samples, except the new oil, were obtained from three in service power transformers which have been working continuously without maintenance for different periods and designated as transformer (1), (2) and (3). Transformers (1) and (2) have been in service for 33 years while transformer (3) has been in service for ten years. Oil sample "A" was taken from transformer (1) and then purified for 50 cycles using the standard purification plant EOK2000 [7]. A method well known and in use is that of filtering and vacuum drying. While under a vacuum of about 1 kPa, the liquid is heated to about 30 to 60 °C, high above the boiling point of water at such a reduced pressure. With large transformer oil surfaces exposed to the vacuum, it becomes freed from its moisture content and dissolved gases [8]. Also, deposit sample "C" was obtained from the deposits found on the surface of the insulated conductors of transformer (1). Oil sample "B" was obtained from

transformer (3) while oil sample "E" and deposit sample "D" were obtained from transformer (2). The new oil samples were taken from unused transformer oil. Some of the physical, chemical and electrical properties for all oil samples are given in Table (1). The breakdown voltage in this table is determined by using the standard IEC-156 test [9]. Also, the electrode specifications, rate of increasing the ac voltage, the number of repeated tests and the method for calculating their average are specified in Ref. [9]. Water content is specified as a mass ratio expressed in part per million (P.P.M.). [10]. The total acidity in mg KOH/g of oil is measured experimentally by using neutralization process [11]. The method of measuring the ash content is described in Ref. [12]. Transformer oil viscosity is determined as given in the ASTM designation [13].

2.2 Atomic absorption spectrometer analysis of deposits

The deposit samples "C" and "D" have been analyzed by atomic absorption spectrometer. The apparatus used is UNICAM 929 AA spectrometer Solar™, England. This analysis gives the type and amount of the metals dissolved in the deposits.

2.3 Infrared analysis of transformer deposits and oil samples

Infrared analysis of the deposits and transformer oil samples have been carried out. The apparatus used to carry out this analysis is type UNICAM 1000, MATTSON 1000 FTIR Spectrometer Solar™, England. A brief description of the operation of this device will be reviewed. After the sample has been put into the cell of the apparatus such that it makes a thin film over the surface of the cell. The cell is introduced in its position in the apparatus. The cell is subjected to the beams to determine the constitution of the sample. The constitution of the sample is determined by the infrared absorption spectra. A complete explanation of the operation of the apparatus and analysis of the infrared spectra can be found in Ref. [14,15]. The results of the sample analyses will be given in a later section.

Table I : Some of the physical, electrical and chemical properties of oil and deposit samples.

PROPERTIES	OIL SAMPLE "A" Whose Deposit is "C"		OIL SAMPLE "B"	OIL SAMPLE "E" Whose Deposit is "D"	NEW OIL
	BEFORE PUR	AFTER PUR			
BDV (KV) [9]	13	74	37	40	42
WATER CONTENT (PPM) [10]	85	8	41	42	15
TOTAL ACIDITY mg KOH/g OIL [11]	0.195	0.006	0.074	0.32	NEUTRAL
ASH CONTENT PERCENT [12]	0.17	NIL	NIL	NIL	NIL
VISCOSITY AT 50 °C ENGLER [13]	1.65	1.6	1.7	1.7	1.5

2.4. BDV of deposits contaminated transformer oil samples

The deposits which have been investigated by atomic absorption spectrometer for their metallic constitutions and b infrared analysis for their functional groups [14] are used separately as contaminants to be added to the new transformer oil samples and to the aged oil sample designated as "A" before its purification. The properties of the new and aged oil are given in Table (I). The contaminants are added by volumetric ratios. The breakdown voltage has been determined by the standard IEC 156 test [9]. The apparatus used to determine the BDV is Foster OTS80AF with automatic voltage rise up to 80 KV [16].

3. RESULTS AND DISCUSSION

3.1. Atomic absorption spectrometer analysis

Deposit samples "C" and "D" are deposits taken from the surface of the transformer conductor insulation. The results of atomic absorption spectrometer analysis of the deposits "C" and "D" showed that the metallic contents of the two deposits are completely different. The metallic content of deposits sample "C" was found to be iron particles with a weight ratio of 150 PPM. The deposits sample "D" has been found to have copper particles with a weight ratios of 150 P.P.M. The

metallic particles are formed in the samples due to the different operating conditions under which the transformers may have been operating. The iron particles are formed in the transformer due to oil oxidation and the subsequent reaction with transformer tank. The copper particles are formed in the transformer oil due to high acidity which corrodes the copper terminals. This will be explained in a later section by the chemical considerations. The difference in the metallic particles of deposits gives an indication of the course of the conditions under which the transformers have been operating. The analysis of the deposits can be used to diagnose the operating conditions to which the transformer has been subjected. The metallic particles deposited on the conductor insulation may form a thin film or metallic spots which may act as a metallic sheath and form with transformer conductors some kind of stray capacitances. This capacitance will result in a stray current which will produce extra heating effects also the heat transferred from the transformer conductors will be affected by the deposit. The acidities of deposit samples "C" and "D" have been determined and have been found to be 0.35 mg KOH/ g oil and 0.5 mg KOH/g oil respectively. The acidities of their corresponding transformer oils as given in Table (I) are 0.195 mg KOH/g oil and 0.32 mg KOH/g oil respectively. The deposits have higher ratios of acidity. This makes the effect of deposit acidity on the transformer coils' insulation more dangerous than

the effect of the transformer oil itself. The increase in the acidity of the transformer oil is detected by the increase in the transformer oil temperature but the acidity present in the deposits can not be detected without analysis. Added to this the deposits are adhered to the conductor insulation which intensifies their deterioration effects. Therefore the inspection of deposits acidity or even the removal of deposits when the transformer oil acidity exceeds certain limit may be an imperative recommendation for the elimination of the deterioration of transformer conductors' insulation.

3.2. Infrared analysis of oil sample "A"

The infrared spectrum of the oil sample "A" is given in Figure (1). It gives the groups which constitute a typical transformer oil. The abscissa of this figure is the wave number in cm^{-1} . The ordinate is the transmittance percent. This method of analysis is intended for the determination of the functional groups and the constitution of transformer oil. Therefore it has been used to distinguish between the constitution of transformer oil samples and to detect the degradation of oil due to aging effects. Figure (1) is usually explained with standard tables and charts [14 -15]. It is necessary to state that this analysis gives an indication of the included functional groups but not quantities analysis. The main functional groups and the distinct peaks are designated on the figure by the alphabetic symbols. The groups at each wave number or range of wave numbers which have been specified in Figure (1) are explained in Table (II). This figure and Table (II) will be used as a base for comparison to which the infrared analysis of different transformer oil samples and deposits will be referred.

3.3. Infrared analysis of oil sample "B"

Figure (2) is the infrared spectrum of sample "B". Comparing Figure (2) with Figure (1) it can be seen that the main functional groups of the transformer oil are obtained in both curves but the difference is obvious at a wave number of $\sim 750 \text{ cm}^{-1}$. The identification of this wave number is given in Table (III). It is necessary to mention that the rest of functional groups corresponding to the wave

numbers of Figure (2) which have been given the same designation as in Figure (1) are identified in Table (I). In mineral oil it is mainly the content of polyaromatic that affects the gassing tendency and the gassing behaviour differs from one oil to another. The appearance of the group identified in Table (III) which is aromatic substitutions may be due to the mixing effect of two transformer oils having different bases and the aging effects. Mixing is an unavoidable because the level of oil in transformer tank has got to be kept and after some time the decrease in the transformer oil will be compensated by adding new transformer oil which might be different than the original one. In fact this oil is mainly a Diala B which has a paraffinic base and has been supplied by an amount of Aral oil which has a naphthenic base. Oil of the naphthenic group has good gas absorbing properties [8]. The presence of aromatic compounds affects the absorption of gases in the transformer oil. The gassing in transformer oil is subjected to standard specifications which prescribe its maximum limit, for example BS 148 [17] and ASTM D3487 [18]. It has been shown in literature that aromatics adversely affect the electrical properties [19]. Also certain aromatic compounds act as a natural inhibitors of oxidation and suppress the evolution of gases [20]. Therefore the variation, reduction or elimination of aromatic compounds is decisively depending on the initial constitution of the transformer oil. The infrared analysis therefore revealed the oil compounds which may affect transformer oil behaviour under high voltage and temperature stresses and can not be detected until their adverse effects appear in the violation of the standard test limits. This indicates that a certain deterioration of transformer oil properties has occurred. Usually the effect of mixing is studied by investigating the physical, chemical and electrical characteristics of the mixture. This may be inadequate and the fractional constitution of the individual oils and the mixture should be investigated in order to make sure that the mixture will maintain the essential characteristics of the individual oils. This may be due to the fact that even for the same transformer oil the properties of the whole oil can not be determined from the properties of its components and their concentrations [21].

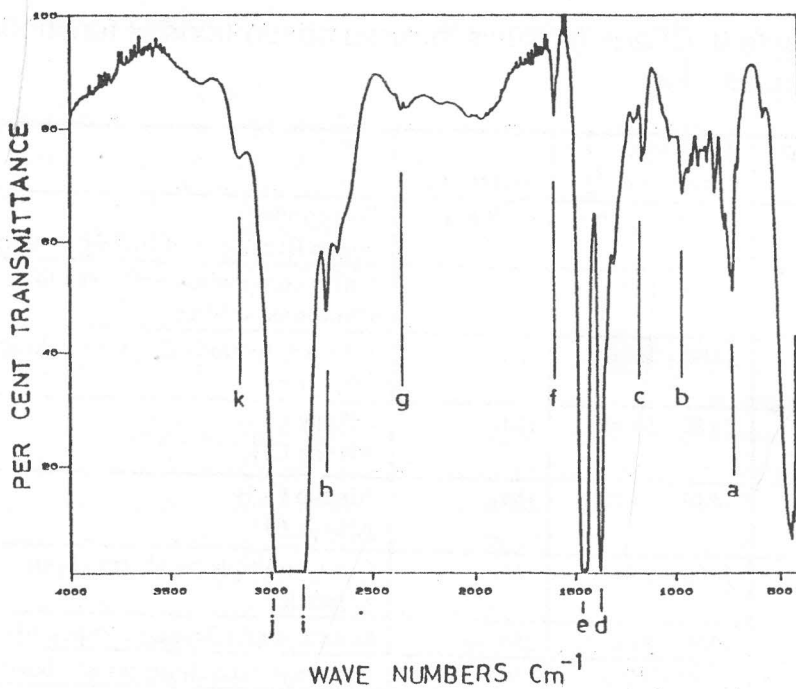


Figure 1. Infrared spectrum of purified transformer oil "A", its functional groups and wave lengths are given in Table (II).

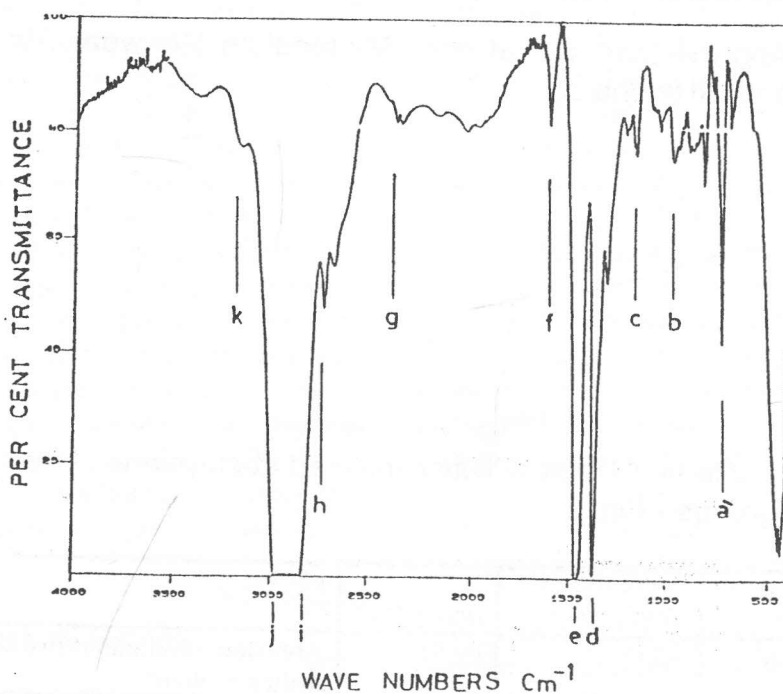


Figure 2. Infrared spectrum of transformer oil "B", its functional groups and wave lengths are given in Tables (II) and (III).

Table II: Characteristics infrared absorptions of functional groups - Fig. 1.

PEAK	WAVE NUMBER RANGE (cm ⁻¹)	INTENSITY*	GROUP
a	~ 750 - 880	(V,S,M)	Polyaromatic : one to five adjacent hydrogen atoms
b	1230 - 1150	(S)	Sulfur compounds S=O stretching vibrations sulfites
c	1400 - 1000	(S)	Wax compounds C - X stretching vibrations
d	1470 - 1430	(M)	Alkane C- H Alkane CH ₃
e	1485 - 1445	(M)	Alkane C- H Alkane CH ₂
f	1600 - 1580	(V)	C = C multiple bond stretching aromatic
g	2260 - 2215	(M)	Unsaturated nitrogen compounds
h	2700 - 2500	(W)	Hydroxyl stretching several bands
i-j	2962- 2853	(M,S)	C - H stretching alkane
k	3650 - 3590	(V,SH)	Alcohols and phenols O- H stretching vibrations free O-H

*Abbreviation: S= Strong, M= medium, W= weak, V= variable and SH= sharp.

Table III: Characteristics infrared absorptions of functional groups - Fig. 2.

PEAK	WAVE NUMBER RANGE (cm ⁻¹)	INTENSITY	GROUP
a'	~ 750	(V,S)	Aromatic substitutions five adjacent hydrogen atoms

3.4. Infrared analysis of deposits sample "C"

Figure (3) shows the spectrum of the infrared analysis of oil deposits "C". The main difference in the functional groups between these deposits and those of the transformer oil sample "A" (Figure (1)) are given in Table (IV). It shows that the appeared functional groups are halogen, esters and sulphur compounds.

3.5. Infrared analysis of deposits sample "D"

The infrared spectrum of deposits sample "D" is given in Figure (4). The identification of the functional groups in this figure is the same as those given in Tables (I) and (IV). As seen from the deposits analysis, the organic functional group constitutions are the same, however the ratios of the individual compounds may be different. The for of these compounds may be due to the oxidation and aging of the transformer oil and the continuous thermal and electrical stresses to which the transformer oil has been subjected. This will be discussed in subsection (3.8). The presence of sulphur or thermally unstable sulphur bearing compounds in transformer oil cause the corrosion of certain metals such as copper immersed in the transformer oil. Oxidation stability and copper discoloration of insulating liquids are measured by standard methods [17] but there is no such test for the deposits. Therefore the formation of deposits whose metallic part is copper may be interpreted as the results of formation of sulphur or unstable sulphur compounds which in turn indicates that the transformer has been subjected to certain types of faulty conditions. Copper discoloration test is intended to detect corrosive sulphur [22]. It is important to indicate that this sulphur compounds affect the electrical properties by decomposition.

3.6. Effect of deposits sample "C" on the BDV of new and aged transformer oil samples

The dependence of the BDV of aged and new transformer oils whose properties are given in Table (I) on the added contaminants is given in Figure (5). The added deposits are given as P.P.M. The breakdown voltage is in KV. From curve "a" it can

be seen that the BDV decreases with the increase in the amount of iron deposits. The percentage decrease in the BDV is given in Table (V). The percentage decrease is calculated at any point referred to its previous value. The table indicates that for the first addition of iron deposits (150 P.P.M.) the percentage decrease is higher than those obtained from the addition of larger amounts of deposits. This means that the breakdown voltage is sensitive to addition of iron deposits. The added deposits should be increased gradually in small steps in order to show the dependence of breakdown voltage on contaminants. In fact the metallic particles can not be created suddenly by large amounts in the transformer which reveals the necessity of investigation of small amounts of contaminants on the breakdown voltage of the transformer oil. Curve "b" shows the effect of adding iron deposits to the new transformer oil. This curve shows that the breakdown voltage of new oil is greatly affected by the iron impurities than the old one. The percentage ratios of decrease in the breakdown voltage of new oil are higher than those of old one for the same amounts of contaminants. This may be due to the fact that the aged (used) oil is contaminated with other impurities than the iron deposits. The iron deposits in this case are not the main factor in the breakdown initiation mechanism. The presence of other impurities which are attracted to the region of high stress [8] and the movement of iron particles may affect distribution of impurities in the high electric stress region and may cause an interaction between impurities and iron deposits which in turn may lead to lower decrease in the breakdown voltage. In addition the initial breakdown voltage of the contaminated oil is relatively low compared to the new one.

3.7 Effect of deposits sample "D" on the BDV of new and aged transformer oil samples

The breakdown voltage of new and aged transformer oil with these deposits as contaminant are shown in Fig. 5. Curve "c" shows that the BDV of the aged transformer oil decreases with the increase in the amount of copper deposits. The percentage decreases are given in Table (V).

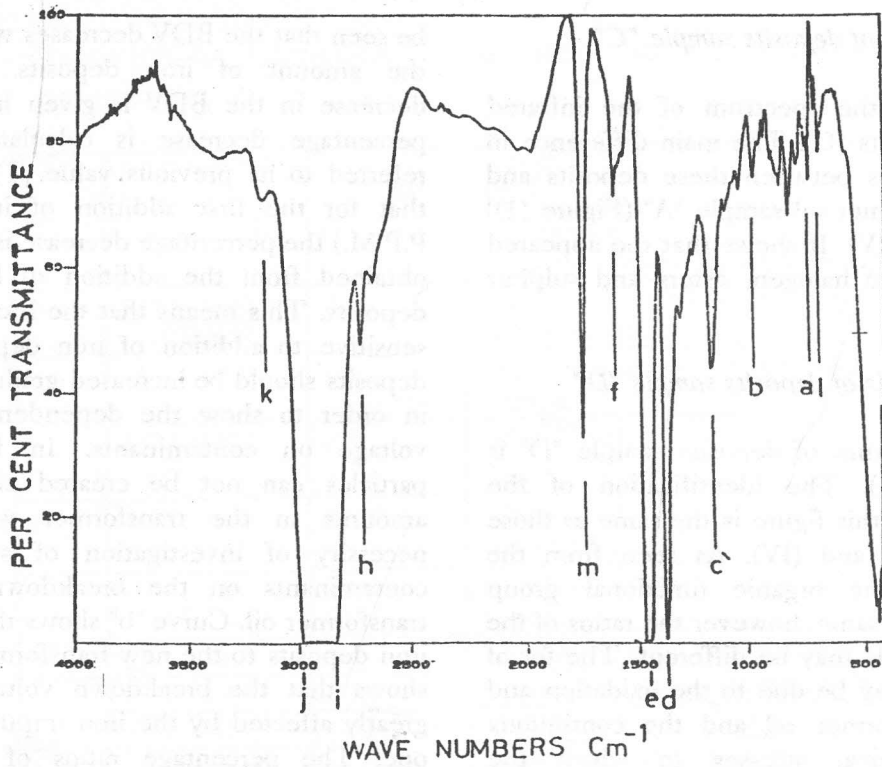


Figure 3. Infrared spectrum of transformer winding deposits sample "C" its functional groups are given in Tables (II) and (IV).

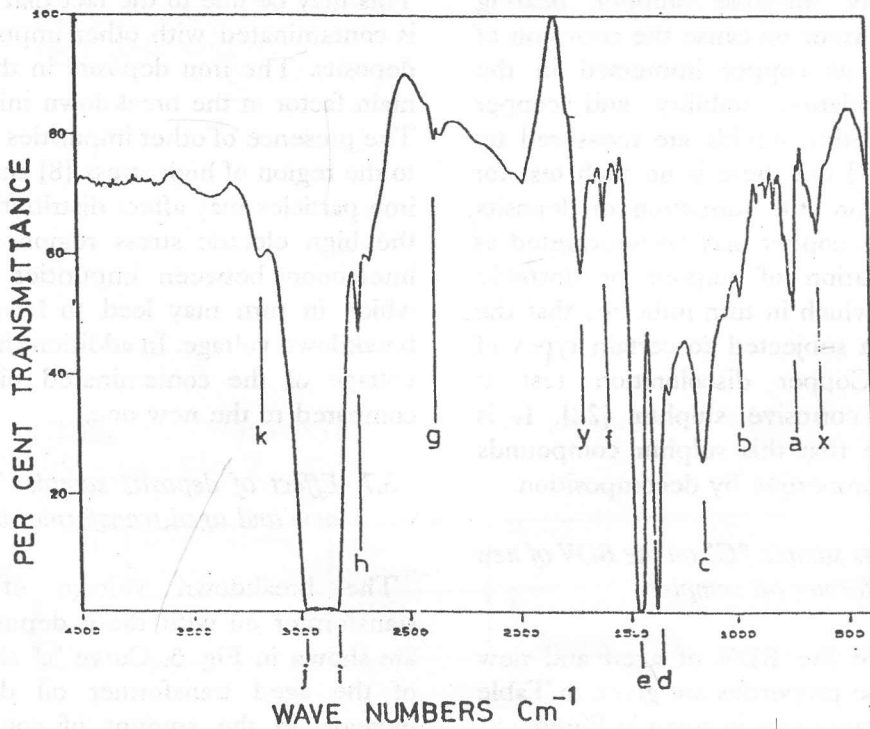


Figure 4. Infrared spectrum of transformer winding deposits sample "D" oil, its functional groups and wave lengths are given in Tables (II) and IV.

Table IV: Characteristics infrared absorptions of functional groups - Fig. 3 and Fig. 4.

PEAK	WAVE NUMBER RANGE (cm ⁻¹)	INTENSITY	GROUP
l, x	650	(S)	Sulfur compounds sulfonic acids
c, c'	1400 -1000	(S)	Wax compounds C- X stretching vibrations
m, y	1750 -1735	(S)	Ester stretching vibration saturated acyclic

Table. V: Percentage decrease in the BDV of new and used transformer oil with the increase in the amount of iron and copper transformer winding deposits

Deposits PPM	IRON		COPPER	
	Used Oil 33 Years	New Oil	Used Oil 33 Years	New Oil
	% Change in BDV	% Change in BDV	% Change in BDV	% Change in BDV
0	0.00	0.00	0.0	0.0
150	9.23	7.14	34.60	19.04
300	6.78	2.56	17.65	11.76
450	9.09	6.65	21.43	5.00
600	10.00	4.23	9.09	7.02
750	8.89	5.88	0.14	1.89

As obtained in the previous subsection the percentage decrease

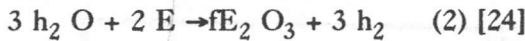
in the breakdown voltage, starts with high value then decreases with further increase in the amounts of deposits. Curve "d" shows that the BDV of the new transformer oil decreases with the increase in the amount of copper deposits. The rate by which the BDV decreases is higher than that obtained from the aged transformer oil. This can be detected from the ratios given in Table (V). Figure 5 and Table (V) show that when the amount of added deposits exceeds certain ratio the used oil is saturated by copper deposits therefore the decrease in the percentage change in the BDV for the large amounts of deposits is noticeable. Comparing the results obtained from new transformer oil for adding iron and copper deposits which are given in Fig. 5 by

curves "b" and "d" it can be seen that the breakdown voltage of the new transformer oil with copper deposits is lower than those obtained from the iron deposits for the same amount of contaminant. The same observation can be obtained from the results of the (used) aged transformer oil which are given by curves "a" and "c". This may be due to the higher conductivity of copper particles than that of the iron particles.

3.8. Chemical interpretation of iron and copper formation

When oil starts to oxidize polar molecules will be formed for example carboxyl, ketones and esters [23]. The oxidation of straight paraffin chain can be proceeded as follows;

In the case of presence of dissolved water content in oil a reaction may occur between dissolved water and iron (especially expansion tank) as follows:

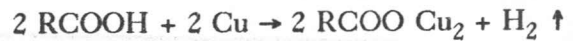
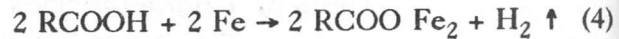


The final result is the formation of ferric oxide. These reactions represent undesirable iron contaminants. Also the oxidation may produce acids as follows:

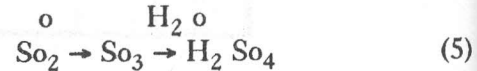


The result of this reaction is the formation of acid compounds (carboxyl and ketones). The presence of carboxyl, iron and copper are catalysts for formation

of esters;



The presence of esters can cause a rise in the temperature of the transformer oil. The formation of sulphuric acid in oil may occur due to the presence of small traces of SO_2 less than 0.1 % in pure liquids. This can be simulated as follows;



The presence of H_2SO_4 acid increases the medium acidity and corrodes the copper and the insulating materials.

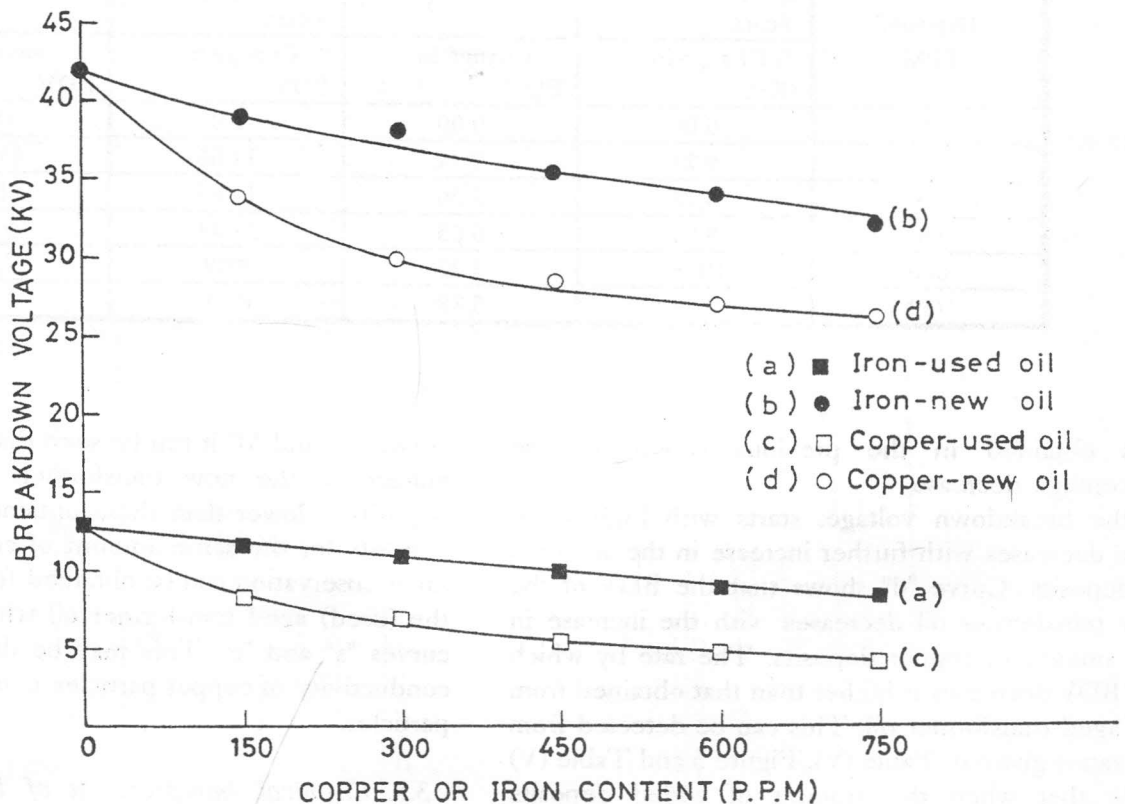


Figure 5. Dependence of the breakdown voltage of new and used transformer oils on the amounts of iron or copper deposits.

4. CONCLUSIONS

The following conclusions could be drawn from this study.

1. The transformer oil and deposits have the same main functional group constitutions but according to aging certain compounds or acids may appear at a certain wave lengths.
2. The investigation of the fractional composition of transformer oil before mixing may preserve the initial constitutions of each transformer oil and hence their individual and the final properties of the mixture.
3. The acidity in deposits is higher than the acidity in the corresponding transformer oil. That makes the effects of deposit acidity on the transformer windings more dangerous.
4. The difference in the metallic portion of deposits may be due to faulty conditions under which the transformers have been subjected.
5. The new transformer oil is sensitive to iron and copper contaminants as the breakdown voltages decreases with higher rate than the aged oil.
6. The contaminant conductivity affects the breakdown voltage of transformer oils.

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