Transformer Oil Regeneration as a Panacea for Electric Power Utility Company's Equipment Optimization

Lambe Mutalub Adesina, Kamaldeen Saadu, Ganiyu Adedayo Ajenikoko

Abstract**:** ***Power transformers constitute the most costly equipment which often posed constraints to electric power utility companies' management. These transformers develop faults often due to oil insulation problems resulting from poor level of insulation oil, lack of routine maintenance, contamination, age, carbonization arising from system tripping as well as degradation of paper insulation due to ageing. However, the most economical way of maintaining stability in power supply to customers is creating a routine program of transformer oil regeneration for power transformer in the network. This paper therefore presents the optimization process of transformer oil regeneration for electric power utility company equipment. In this study, combined techniques of hot oil circulation, oil purification and oil reclamation of transformer oil regeneration was used for analysis of two 15MVA, 33/11kV power transformer. The process is aimed at drying the solid insulation of the transformer through the circulation of hot oil. The results of the transformer oil test before and after carrying out oil regeneration processes for the two 15MVA transformers are obtained and presented. For each transformer, the results are in five categories of properties namely; Physical, Electrical, Chemical, Dissolved metals and Dissolved gas analysis properties. The results indicated that the viscosity of transformer 1 is better than that of transformer 2. In addition, the dielectric breakdown voltage of oil transformer 1 is of more quality than the oil in transformer 2. The results are in agreement with standard ASTMD, IEC and ISO because the transformer properties has individual standard with each having its own mark. The comparison shows that transformer oil regenerated was very close to reality because the oil in the two power transformers is close to 90 %.***

Index Terms**:** ***Oil Regeneration, Power Transformer, Oil Viscosity, Oil Insulation, Dissolved Metal and Gas, Optimization***

I. INTRODUCTION

Transformers generally play a key role in integrating the power grid and in ensuring continuous operation of the power system's network. Power transformers are better described as the most expensive and important components in power systems namely generation, transmission and distribution system [1]. The reliability of these assets in the aforementioned network lies on availability and profitable operation of such equipment in the system [1] - [3]. Failure of power transformer in network is often accomplished with problems such as cost of lifting up from Plinth into conveying vehicle, cost of transportation to workshop for repair cost as well as estimated revenue lost by utility company due to power outage. However, utility companies' special attention is being given to power transformers in terms of handling, routine and preventive maintenance. By so doing, power outages are being drastically reduced.

Transformer insulation failure is identified as the most dangerous fault that needs special attention. Good transformer insulation is associated with quality transformer oil contained in it. One of the parameters associated with this quality include oil of reliable dielectric strength whose breakdown voltage ranges between 60-70kV. For mineral oil, a generally accepted maximum moisture contents is 35 part per million (PPM) [4]. In addition, the power factor of insulating oil equals the cosine of the phase angle between an AC voltage applied and the resulting current. A high power factor in service- aged oil indicates deterioration, contamination or both, with moisture, carbon or deterioration products. Thus, for mineral oil, the power factor of new oil should not exceed 0.05% at 25^{o}C [3] – [4].

Furthermore, the degree of aging or degradation of the insulation system i.e. conductor insulation, winding insulation (such as oil, core and fluid insulations) are assessed by interfacial tension, acid neutralization and colour changes. A significant change in these parameters also indicates overheating of all or part of the insulation system.

II. POWER TRANSFORMER INSULATION AND ITS AGEING

A. Transformer Insulation

The insulation in power transformers consist of two different types, the oil and cellulose (Paper/Pressboard) insulations. Oil in the transformer serves as insulation strength, functions as a coolant and an information career which can be used for condition or health diagnostic purpose.

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This study focuses on mineral oils, which are used extensively in transformers for over a century [5] – [9]. Mineral oils are composed of refined hydrocarbon based oils with additives to improve the performance. Typical example of such additive is the inhibitor, which curtails 'oxidation' process and thus increasing the life of the oil. Crude oil comprises hydrocarbon compounds as well as smaller quantities of compounds such as Sulphur, Oxygen,

Nitrogen and Iron etc [10]. Mineral oil is a by-product of the distillation of the crude oil, and can be classified into three types as Paraffinic, Naphthenic and Aromatic [9], [11]. Among all, Naphthenic oils are often used due to abundance, lower pour point and higher solubility of sludge [11].

On the other hand, Solid insulation (paper) transformers consist of cellulose and are present in the form of paper and pressboard. It provides electrical insulation to the winding and mechanical support to the winding for stability. Insulation grade paper is made from wood by the Kraft process or sulphate process [9], [11]. About 90% of this paper is Cellulose, 6-7% is Lignin and the rest is Pentosans [9]. In power transformers, cellulose exists mainly in the form of Kraft paper and Pressboard. Kraft paper insulator is wrapped over the conductors and consists of cellulose, hemicelluloses and residual of thiolignin and remnants of the paper pulping process [10]. Cellulose consists of the B-D-glucopyranosil units which occur in the form of linear polymeric chain. The number of such chains is represented by the Degree of Polymerisation (DP). Cellulose can be represented as $[C_5 H_{10} O_5]$ n, where 'n' represents the DP [12]. Higher value of n implies a higher mechanical strength of the paper. However, the sulphate process results in slightly alkaline residue in paper due to the sulphate contents. Quality and strength of the paper produced vary widely between manufacturers, who employ different technologies and processes for production [13].

B. Ageing of Power Transformer Insulation

Oil in power transformer is expected to last for as long as the transformer does. As oil and paper age, they generate degradation products. IEEE loading guide for Mineral Oil Immersed transformers defines end-of-life of a transformer as based on measurable mechanical, dielectric and chemical characteristics [14]. Consequently, the ageing of a power transformer can generally be discussed under the following categories; Transformer Oil Ageing (TOA), Transformer Paper Ageing (TPA), Ageing of Oil-Paper Insulation (AOPI) and Transformer Ageing Indication (TAI).

On TOA, the ageing process is the degradation of the hydrocarbons in the oil which can be caused by several factors such as exposure to air, high operating temperatures, atmospheric moisture ingress and presence of metallic compounds such as iron, copper and lead [7]. The degration process is triggered by the appearance of a hydrocarbon radical called initiation stage. The next stage is propagation, where the hydrocarbon radical reacts with any oxygen present to form Peroxy radical. The peroxy radical can then further react with existing hydrocarbon molecules to form hydroperoxide. The final stage of oxidation is termination, where the hydroperoxides degenerate to form ketones and alcohols, which in turn lead to organic acid formation or an aldehyde leading to resin formation. Thus oil oxidation can cause deposit (sludge) formation, oil thickening, lacquering and an increase in oil acidity [10]. Factor affecting oil ageing include, oxygen, water/moisture, temperature, presence of metal, and inhibitor content.

On TPA, the ageing process of cellulose can be summarized as three mechanisms, hydrolysis, oxidation and pyrolysis. Acid-catalysed hydrolysis is the major mechanism of paper ageing in a transformer [10] – [14]. Hydrolysis involves the cleavage of hydrogen, described as a catalytic reaction with the aid of the acid by-products of both oil and cellulose degradation [13, 14]. Water is considered more imperative to the ageing process when compared to oxygen, thus making hydrolysis the dominating ageing mechanism of paper. Oxidation mechanism will commence once the hydroxyl in cellulose structure are attacked by oxygen, which weakens the glycosidic linkage. Moisture is the primary ageing product through oxidation, while secondary ageing products include carbonyl and carboxyl groups. These groups will promote hydrolysis in paper and oil [4, 14]. Pyrolysis mechanism is a form of 'slow combustion' defined as the thermal degradation of the material at elevated temperatures in the absence of oxygen. Pyrolysis doesn't greatly affect the ageing of a transformer as it normally occurs at temperature of over 140^{o}c. Thus, unless a fault develops, the effect of pyrolysis on paper ageing can be deemed to be insignificant. In summary, ageing of paper is influenced primarily by 4 factors; water, moisture, acid and temperature.

On AOPI system in transformers, the ageing of solid insulation is comparatively more influential on the age of the transformer. This is because oil can be purified/reclaimed when necessary. But, paper and other solid insulation components forms irreplaceable part of the transformer. Factor such as thermal, chemical, mechanical and electrical stresses influence the ageing of paper and oil [1]. The by-products of oxidation include water and acids of the carbonyl and carboxyl type [10] – [14], the latter of which is classified as LMA and HMA. Water aids in the dissociation of the LMA by increasing the H^{+}ion content in the system, thus leading to hydrolysis of the paper.

The effects of ageing of transformer via oil and paper insulation exist as chemical by-products or affect intrinsic electrical and physical parameter of the insulation. Although IEC 60422 and IEC 60554 standards provide benchmark for the evaluation of the transformer condition through the testing oil and paper properties respectively. In practice, evaluation methods may cover chemical, physical and mechanical properties of the oil and paper. Commonly used chemical ageing indicators include Acidity, Water/Moisture, Furanic contents and Methanol [14]); while the physical and mechanical ageing indicators include colour and appearance of oil, Degree of Polymerisation of paper and Tensile strength of paper.

C. Transformer Oil Regeneration Techniques

Power System operators rely greatly on several intervention techniques which would not only improve the system performance but also contribute to reduced cost. Depending upon the size and location of the transformer in the power system operators, one or any combination of different techniques listed below may be used.

It includes; oil purification method, on-load drying by molecule service (ODMS), absorbent-based reclamation, hot oil circulation, hot air circulation, vapour phase drying (VPD), hot oil spray (HOS), lower frequency heating (LFH) and comparison of solid insulation dry-out technologies.

III. MATERIALS AND METHOD

In this study three techniques of transformer oil regeneration were combined to achieve the following goals :

1. Pre-oil regeneration tests on sample oil are carried out. These tests include, Dielectric breakdown voltage, Moisture content and Power factor
2. Oil regeneration process is meticulously followed from start to the end using the selected technique
3. Various tests carried out are repeated when regeneration oil is completed as post- oil regeneration.
4. Comparison is drawn between the tests results obtained.

Hot oil circulation technique of oil regeneration was adopted and its details are presented in the flowchart shown in Figure 1. The process is aimed at drying the solid insulation of the transformer through the circulation of hot oil. This process is conventionally accompanied by oil purification and oil reclamation as shown in Figure 2. Oil purification is the simplest form of reconditioning the oil. It involves passing the oil through a filter element and removing all suspended particles and impurities in the oil. The level of purity achievable varies with the size and type of filter used or contained in the oil treatment plant. At this point, an absorbent bed (fuller's earth or Alumina) is added to remove the acidic components and other degradation by-products from the oil through absorption. The result is dried and degassed in the vacuum chamber at a temperature above boiling point of water. The process removes all moisture while absorbent bed addition also removes the oxidation inhibitors from the oil, so it is necessary to re-inhibit the oil once the process is completed. At the end of the process, materials including acids, alcohols, aldehydes, ketones, esters, soaps and aromatic material (in case of uninhibited oil) are removed.

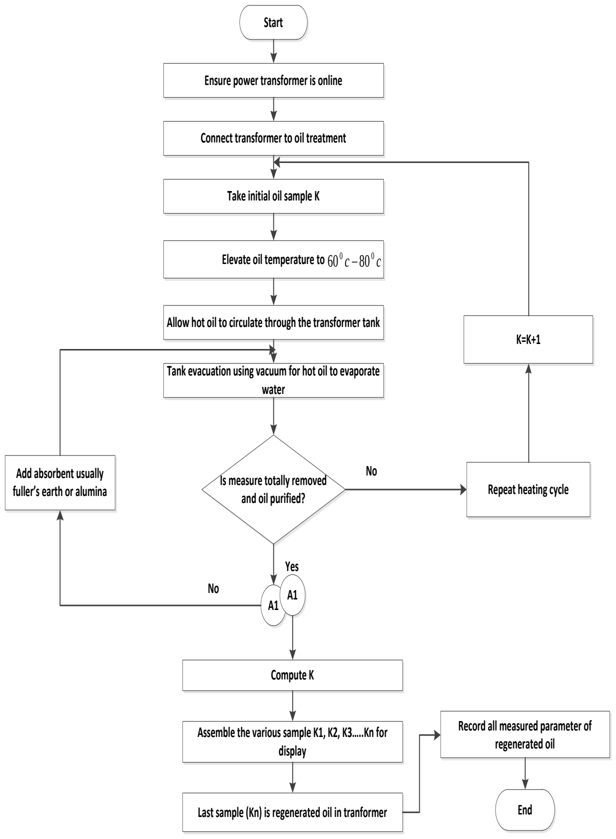

Figure 1: Flowchart of oil regeneration using hot oil circulation, purification and absorbent based techniques

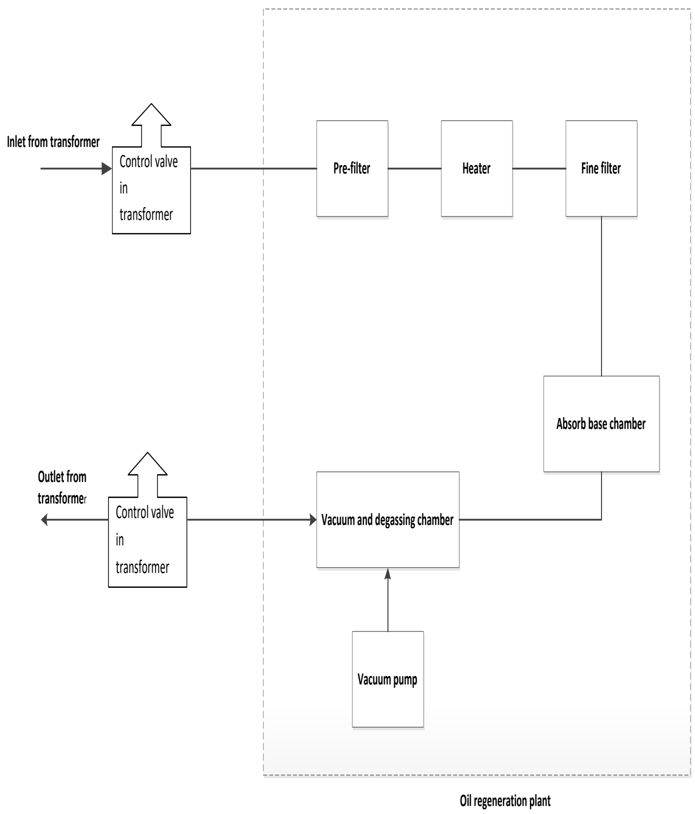

Figure 2: Schematic Diagram of Oil flow in Oil Treatment Plant

IV. DISCUSSION OF RESULTS

The results of the transformer oil test before and after carrying out oil regeneration processes for the two 15MVA transformers are presented in Figure 3 to 12. For each transformer, the results are in five categories of properties namely; Physical, Electrical, Chemical, Dissolved metals and Dissolved gas analysis properties. Majority of these properties have individual standard they complied with such as ASTMD, IEC, ISO, among others. These standards form the bench mark with which the property's current value can be compared with. The more closely this value to the specified standard the more reliable the property is.

Figure 3 shows the physical property test of transformer oil before and after carrying out regeneration processes of transformer 1. From Figure 3, the initial colour of the transformer oil before and after oil regeneration is 5.5 and 1.0 L respectively. This indicates that the oil before regeneration has spoilt beyond the maximum specification of 5 L and after regeneration; the colour of transformer oil was recorded to be sparkling yellow. The transformer temperature flash point ranges from 168 ^{0}C to 166 ^{0}C before and after oil regeneration while the value of interfacial tension at 25 ^{0}C temperature is 35.8 and 46.2 millinewton/meter before and after oil regeneration respectively. More so, the relative density of the transformer ranges from 0.8755 to 0.8743 before and after oil regeneration respectively. Thus, density of the transformer varies with temperature and pressure. In addition, the values of specific gravity after the oil regeneration process were slightly reduced. Also, the kinematic viscosity measurement at 40 ^{0}C are 13.51 and 12.87 m^2/s, and at 100 ^{0}C, the valuesare 2.994 and 2.926 m^2/s before and after oil regeneration respectively.

Temperature control is the most important parameter for obtaining accurate and precise kinematic viscosity measurements. Thus, a slight variation in temperature can have a very large effect on the viscosity of a fluid. The bath temperature for the most common measurements, 40 and 100 ^{o}C must be controlled to within ± 0.02 degree centigrade. This value is extremely light window and thus great care was taken to achieve this control. The percentage reading of the transformer after oil regeneration to that of before oil regeneration are 95.3% and 99.7% at 40 and 100 ^{o}C respectively. This implies that the viscosity of the transformers was not too bad prior to regeneration. The determination of sediment and soluble sludge in service – aged insulation oils is intended primarily for oils of comparatively low viscosity. The sludge ranges from 0.014 to 0.009 before and after oil regeneration. The difference between sludge obtained before and after oil regeneration is 0.005%.

The electrical property test of transformer oil before and after carrying out oil regeneration processes of transformer 1 is shown in Figure 4. From Figure 4, the dielectric breakdown voltage of the oil improved from 21 kV to 40 kV. This implies that the oil in the transformer becomes more quality after oil regeneration. Dissipation factor (or Loss factor) is a measure of dielectric losses in an electrical insulating liquid when used in an alternating electric field and of the energy dissipated as heat. A low dissipated factor or power factor indicates low AC dielectric losses. Therefore, at the specified temperature of 25 and 100 ^{o}C, the dissipation factor of the transformers reduced from 0.45 to 0.10 and 9.32 to 2.5 respectively.

Figure 5 displays the chemical property test of the transformer oil before and after carrying out oil regeneration processes of transformer 1. From the Figure, the oxidation stability increased from 41 to 43 minute. The oxidation of electrical characteristics of an insulating liquid is affected by excessive water content. High water content may make a dielectric liquid unsuitable for some electrical applications due to deterioration of properties such as the dielectric breakdown voltage. The total acid number in the transformer reduces from 0.288 to 0.01 mgKOH/g after oil regeneration. This indicates a non-corrosive sulphur content in the transformer. The moisture content reduced from 74.38 to 22.11 ppm after oil regeneration. The PCB content of the transformer also reduced from 28 to 27 mg/kg after oil regeneration. The results indicate that after regeneration exercise, the total furfural also reduced drastically from 12.17 to 5.09mg/kg.

For the dissolved metals for transformer 1, this involves the determination of metals and contaminants in insulating oils by inductively coupled plasma atomic emission spectrometry. The result is shown in Figure 6. From the results, aluminium reduces from 0.43 to 0.22 mg/L after oil regeneration. The cadmium values increase from 0.03 to 0.19 mg/L after regeneration. Copper content of the transformer increases from 0.10 to 0.18 after regeneration. In addition, iron, lead, nickel, sodium, tin and tungsten are reduced to less than 1 mg/L after oil regeneration. While silicon and zinc reduces their content value after oil regeneration, silver content of the transformer increase from 0.13 to 0.14 mg/L after oil regeneration.

Figure 7 shows the dissolved gas analysis in electrical oil testing before and after carrying out oil regeneration processes of transformer 1. The test method covers three procedures for extraction and measurement of gases dissolved in electrical insulating oil having a viscosity of 20cst or less at 40^{o}C (104^{o}F), and the identification and determination of the individual component gases extracted. The nitrogen content of the gas increases from 427587.797 to 53610.07 ppm after regeneration. The oxygen content of the gas reduces from 123017.058 to 18186.773 ppm after regeneration. Carbon dioxide ranges from 3374.412 to 230.797 ppm which shows a reduction of the gas content in the transformer after oil regeneration. Hydrogen, methane, ethane, ethylene and acetylene content in the transformer were less than 1 ppm after oil regeneration processes. The total combustible gases was reduced from 173.776 to 33.581 ppm likewise the total dissolved gases of the transformer was reduced from 554060.243 to 72061.22 ppm after regeneration.

The physical property test of transformer oil before and after carrying out regeneration processes of transformer 2 is depicted in Figure 8. From the Figure, the initial colour of the transformer oil before and after oil regeneration is 5.5 and 1.5 L respectively. This indicates that the oil before regeneration has spoilt beyond the maximum specification of 5 L and is brownish in colour, and after regeneration; the colour of transformer oil was recorded to be yellow.

The transformer temperature flash point reduces from 156 ^{0}C to 152 ^{0}C after oil regeneration while the value of interfacial tension at 25 ^{0}C temperature is 36.7 and 47.4 millinewton/meter before and after oil regeneration. The relative density of the transformer reduces from 0.8755 to 0.8743 after oil regeneration. Thus, density of the transformer varies with temperature and pressure. In addition, the values of specific gravity after the oil regeneration process were slightly reduced. Furthermore, the kinematic viscosity measurement at 40 ^{0}C is 9.930 and 9.897 m^2/s, and at 100 ^{0}C, the value is 2.994 and 2.45 m^2/s before and after oil regeneration respectively. Thus, a slight variation in temperature can have a very large effect on the viscosity of a fluid. The bath temperature for the most common measurements, 40 and 100 ^{o}C must be controlled to within ± 0.02 degree centigrade. The percentage reading of the transformer after oil regeneration to that of before oil regeneration are 97.7% and 83.6% at 40 and 100 ^{o}C respectively. This implies that the viscosity of the transformers was not too bad prior to regeneration. The sludge of the transformer also reduces from 0.013 to 0.008 after oil regeneration.

Figure 9 indicates the electrical property test of transformer oil before and after carrying out oil regeneration processes of transformer 2. The dielectric breakdown voltage of the oil improved from 25 kV to 34 kV. This implies that the oil in the transformer becomes better after oil regeneration. At the specified temperature of 25 and 100 ^{0}C, the dissipation factor (loss factor) of the transformers reduced from 0.63 to 0.14 and 12.4 to 2.54 respectively after oil regeneration.

Figure 10 displays the chemical property test of the transformer oil before and after carrying out oil regeneration processes of transformer 2. The oxidation stability increased from 43 to 113 minute. The total acid number in the transformer reduces from 0.299 to less than 0.01 mgKOH/g after oil regeneration. This indicates a non-corrosive of sulphur content in the transformer. The moisture content reduced from 59.72 to 32.46 ppm after oil regeneration. The PCB content of the transformer also reduced from 4 to less than 2 mg/kg after oil regeneration. The results indicate that after regeneration exercise, the total furfural also reduced from 3.29 to 0.76 mg/kg.

Figure 11 displays the dissolved metals test of transformer oil before and after carrying out oil regeneration processes for transformer 2. This involves the determination of metals and contaminants in insulating oils by inductively coupled plasma atomic emission spectrometry. From the result, aluminium reduces from 0.47 to 0.03 mg/L after oil regeneration. The cadmium value reduces from 0.45 to 0.22 mg/L after regeneration. Copper content of the transformer reduces from 0.12 to 0.057 mg/L after regeneration. While iron, silicon, silver and zinc reduce their content value after oil regeneration, nickel content of the transformer increase from 0.10 to 2.30 mg/L after oil regeneration. In addition, lead, sodium, tin and tungsten are reduced to less than 1 mg/L after oil regeneration.

Figure 12 shows the dissolved gas analysis in electrical oil testing before and after carrying out oil regeneration processes of transformer 2. The test method covers three procedures for extraction and measurement of gases dissolved in electrical insulating oil having a viscosity of 20cst or less at 40^{o}C (104^{o}F), and the identification and determination of the individual component gases extracted. The nitrogen content of the gas increases from 418845.27 to 70044.46 ppm after regeneration. The oxygen content of the gas reduces from 124585.778 to 26899.33 ppm after regeneration. Carbon dioxide ranges from 2908.453 to 344.451 ppm which shows a reduction of the gas content in the transformer after oil regeneration. Methane reduces from 100.803 to 23.82 ppm after oil regeneration. While, hydrogen, ethane, ethylene and acetylene content in the transformer were less than 1 ppm after oil regeneration processes. The total combustible gases reduced from 190.625 to 23.82 ppm likewise the total dissolved gases of the transformer reduced from 127684.856 to 97312.06 ppm after regeneration.

In general, it was observed that the percentage reading after to that of before oil regeneration implies that the viscosity of the two transformers were not actually too bad prior to regeneration. But, viscosity of transformer 1 is better than that of transformer 2. In addition, the difference between sludge obtained before and after is 0.005% and this value was the same for the two transformers. The dielectric breakdown voltage of oil in transformer 1 is of more quality than that of the oil in transformer 2.

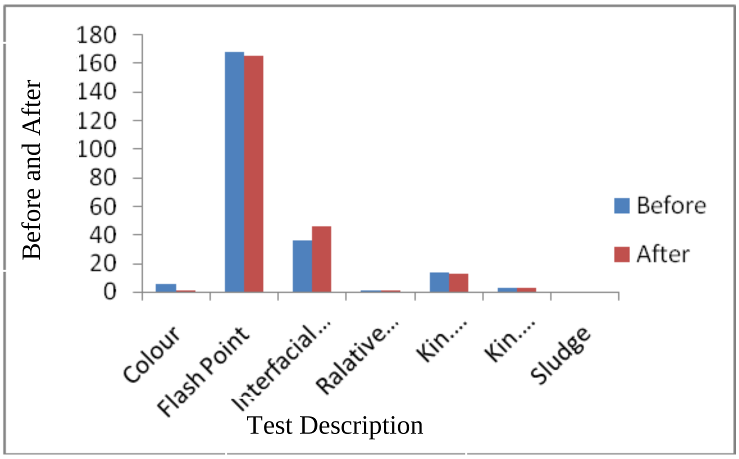

Figure 3: Physical property test of transformer oil before and after carrying out oil regeneration processes for transformer 1

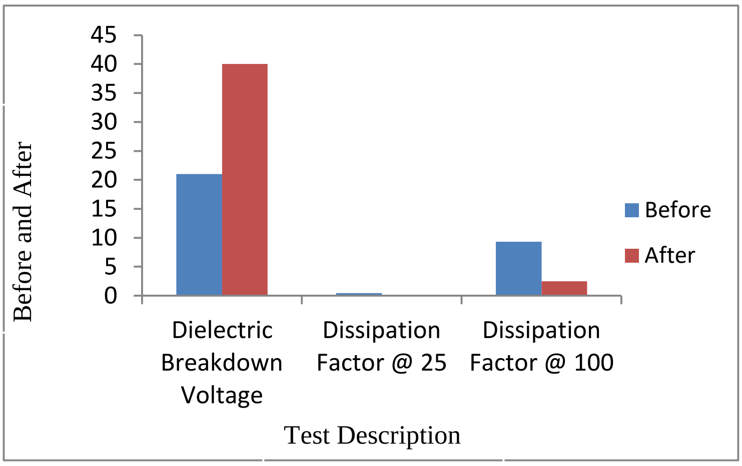

Figure 4: Electrical property test of transformer oil before and after carrying out oil regeneration processes for transformer 1

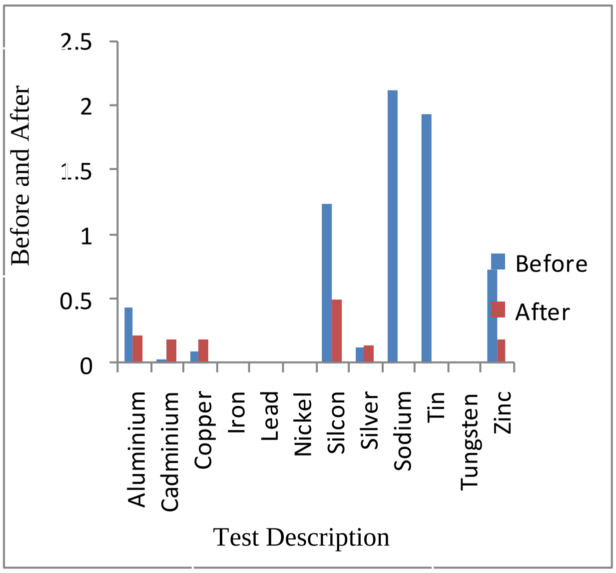

Figure 6: Dissolved metals test of transformer oil before and after carrying out oil regeneration processes for transformer 1

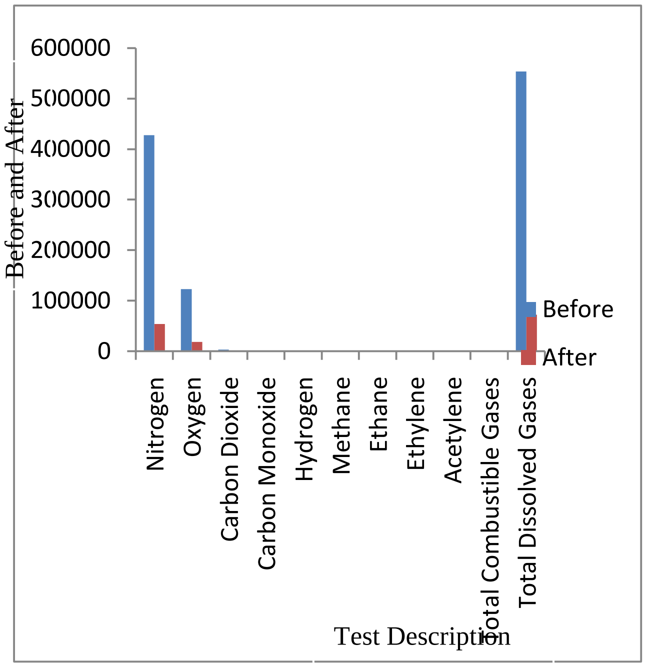

Figure 7: Dissolved Gas Analysis (DGA) in electrical oil testing before and after carrying out oil regeneration Processes for transformer 1

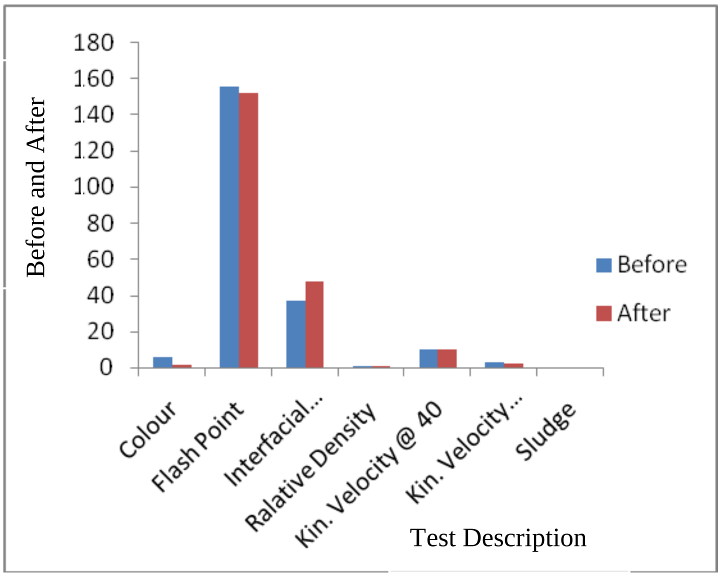

Figure 8: Physical property test of transformer oil before and after carrying out oil regeneration processes for transformer 2

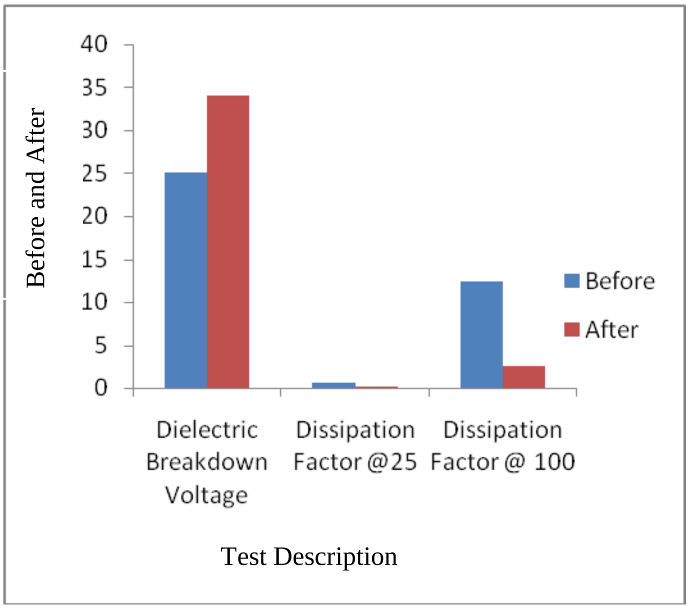

Figure 9: Electrical property test of transformer oil before and after carrying out oil regeneration processes for transformer 2

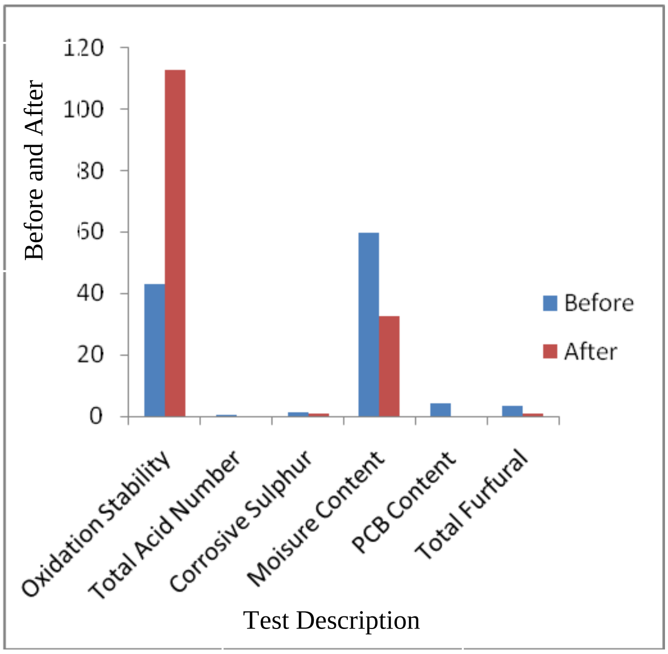

Figure 10: Chemical property test of transformer oil before and after carrying out oil regeneration processes for transformer 2

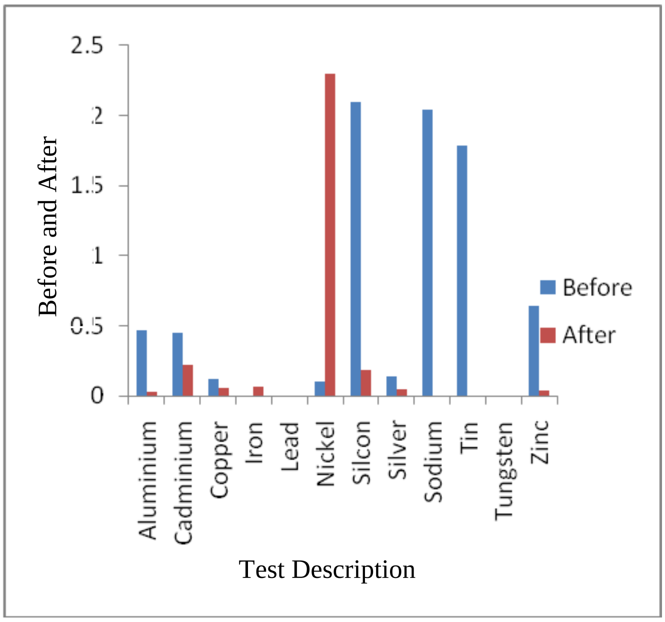

Figure 11: Dissolved metals test of transformer oil before and after carrying out oil regeneration processes for transformer 2

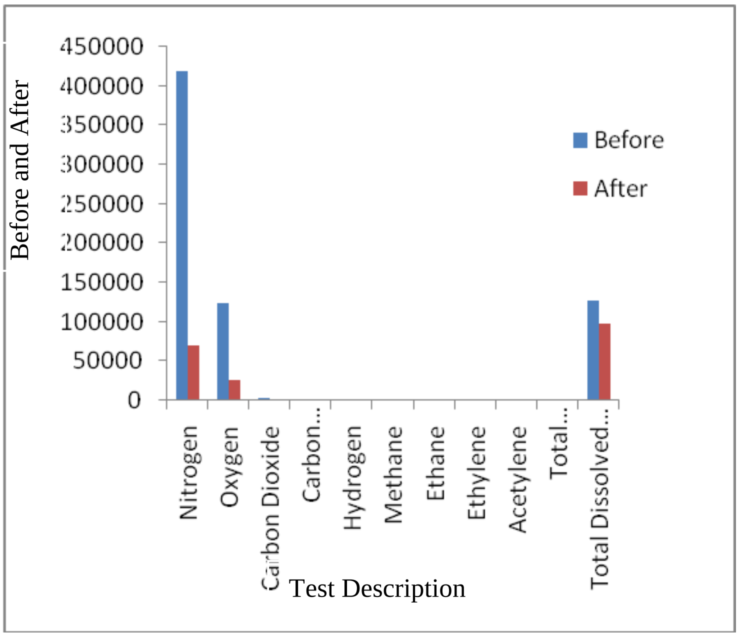

Figure 12: Dissolved Gas Analysis (DGA) in electrical oil testing before and after carrying out oil regeneration Processes for transformer 2

V. CONCLUSION

This paper has reviewed power transformer and its aging process. It focused on mineral oils used in power transformers. The problems that are often associated with transformer oil insulation were identified and discussed. The best approach to solution of poor oil insulation was identified via literature review as combined techniques of hot oil circulation, oil purification and oil reclamation for oil regeneration. This combined technique was applied to two numbers 15MVA, 33/11kV power transformers selected from a network of a reputable power utility company in Nigeria as case study. However, since these properties have individual standard they complied with such as ASTMD, IEC, and ISO among others, with each having its own mark; the results obtained from this research were compared with these bench marks. The comparison shows that transformer oil regenerated was very close to reality because the new oil in the two power transformers is close to 90 percent new.

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