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Enhancing Service Life of Power Transformer through Inhibiting the Degradation of Insulating Oil by New Approach

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***Abstract*—** Oil reclamation is a transformer insulation reconditioning technique, which may use as on-line or off-line. However, there is a need of evidence showing the effect of this process on conditions of the paper insulation, which indeed affects the life span of a transformer. This research work focuses on oil reclamation experiment on an old retired distribution transformer. Electrical testing and post-mortem analysis of the transformer were conducted, aimed at investigating the design aspects and collecting information on the insulation conditions prior to the oil reclamation. Temperature and moisture sensors were installed to monitor the conditions within the transformer during the oil reclamation [2]. The experimental process of transformer Oil reclamation was performed into two phases, with regular oil sampling to analyze the changes in key oil parameters, namely acidity number (AN), moisture and breakdown voltage (BV). This was accompanied by paper sampling at the end of each reclamation cycle to study the effects of oil reclamation on properties, particularly moisture, LMA and degree of polymerization.

The transformer which was used for the entire experimental process was about 45 years old, 200kVA, 1100 / 415-240V distribution transformer. In order to study the long-term effect of oil reclamation, oil samples were collected from an on-site reclamation exercise performed in a laboratory-accelerated thermal ageing experiment. Oil samples collected before and after the reclamation were aged alongside new oils for comparison [4]. Through the regular monitoring and measurement of oil parameters (AN, moisture and BD strength) over 144 hours and paper parameters (LMA, moisture and DP) at specific stages of phase 1, it was observed that the transformer oil-paper insulation system was significantly improved.

The entire research work was performed into two phases (phase 1 and phase 2). The “phase 1” was aimed to improve and restore the oil parameters comparable to the parameters of new oil as specified in “IEC-60296” and its effect on the paper insulation. “Phase 2” was aimed to compare the life span of reclaimed oil filled transformer with the transformer in which aged oil has been replaced by new oil[6].

Effective study of oil reclamation was analyzed through laboratory accelerated aging experiment and real time application on a 45 years old transformer. Through the regular monitoring and measurement of oil parameters (AN, moisture and BD strength) over 144 hours and paper parameters (LMA, moisture and DP) at specific stages of phase1, it was observed that the transformer oil-paper insulation system was significantly improved [15]

***Keywords*—** ageing, oil parameters, oil degradation, oil reclamation, paper insulation

I. INTRODUCTION

Transformers are the most essential integrating component of electrical network system. With the world moving towards a more resilient power network, the reliability of each network component becomes of utmost importance in ensuring uninterrupted power supply to the consumers. The study of aging problem of transformers has a great and serious interest, which increase their importance in the power system. These studies help gain valuable insights which could aid in prolonging the life of these assets and maintaining their reliability [1]. Ageing studies are gaining further prominence recently due to the large population of ageing assets in operation.

Market deregulation and an increased competition have urged utility operators to look into optimizing the utilization of their equipment in terms of operating efficiency and cost-effectiveness [2]. In response to this requirement, utility operators and service providers have adopted asset management techniques, targeted at enhancing the usage of the residual life time of the asset, with particular attention to ensuring reliability of service, and distribution of maintenance and re-investment costs. Due to the high value and large population [3], transformers are one of the main assets in the focus of asset management entities.

Now a day the majority of the power transformers, in electrical network are oil immersed, with cellulose as the solid insulation. The oil, apart from functioning as a coolant, also serves as an electrical insulation [8]. The ageing of transformers is generally due to deterioration of the paper and oil insulation system. A utility can exercise various restoration techniques to improve the oil and paper condition by the removal unwanted products. Of these techniques, oil reclamation has recently become more effective to increase the life of power transformers [1, 2].

II. Experimental setup and procedure for Oil reclamation

The oil reclamation process can be split into three distinct processes – drying and degassing, filtering, and fuller's earth reclamation [11]. The labeled diagram of the oil reclamation process is given in Fig. 1. The entire unit is operated through a central control panel, with built-in safety elements and controllers, apart from being provided with a range of alarms and interlocks.

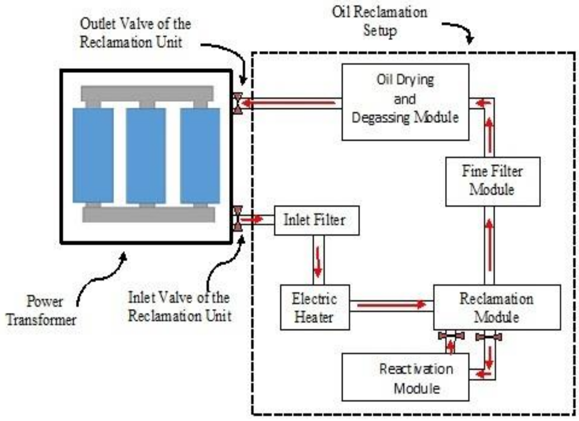

Figure 1. Labeled diagarm of oil reclamtion setup

A. Inlet Filter

At the inlet of the reclamation equipment, a coarse filter is used t remove the particles of about 80 µm or larger. Most of the sludge is filtered at this initial stage. The Inlet filter is replaced immediately after saturation.

B. Electric heater

The oil filtered through inlet filter is passed though a low watt heater of about 1.8 watt/cm$^{2.}$ The electric heater is used to increase the efficiency of the process by aiding easier spreading of the hot oil through coalesces and filters. The heater is designed to heat the incoming oil up to a temperature of 90 °C. The heating element also plays a key role in the removal of chemical ageing by-products, which is executed by the fuller's earth module [14]. The oil passes through a coarse inlet filter before entering the heater, designed to remove suspended particles of size larger than 80µm.

C. Reclamation Module

Reclamation module is the central main part of the oil reclamation process. This module mainly consists of a single column of fuller's earth. This column acts as adsorbent medium for the chemical ageing by-product removal process. The heated oil from the heater module is forced to pass through the fuller's earth columns, where the constituents causing acidity are gradually removed. These columns are reusable after saturation, through a process called reactivation.

D. Reactivation module

The adsorption module of the reclamation setup is the fuller's earth reactivation module. Reactivation of the adsorption medium needs to be initiated manually, at the discretion of the operator. The process consists of burning down the fuller's earth, along with all the adsorbed impurities. The oil present on the surface of the fuller's earth serves as fuel and hence the burning is started by a coil present at the top of the column [12]. The fuller's earth itself has an extremely high thermal capacity and does not get destroyed, regardless of temperatures within the columns reaching up to 700 °C. The exhaust gases produced are passed through an activated carbon column, before being released outside into the atmosphere.

E. Fine filter module

The CJC fine filter is used as primary filter. This filter can remove particles from the oil up to 0.3 µm with high dirt folding capacity. These filters can be replaced easily when get saturated.

F. Drying and degassing module

The drying and degassing of oil is performed by a specially designed welded tank. It consists of equally spaced sheets for equal distribution of oil. The oil is passed through these sheets under a vacuum of 5m bar. Water and other vapors are evacuated by the vacuum pump and then exhausted. This step was aimed to bring the water contents of oil to a level less than 5ppm.

G. Connecting the oil reclamation system to the transformer

The setup for the oil reclamation experiment is shown in Fig. 2. The outlet tap of the transformer is connected to the inlet of the oil processor module through a hose. The first step of oil flow is through the heater module, where the oil temperature is raised to required value [16]. The oil which has been heated is then sent to the fuller's earth column through a rerouting valve installed on the processor module. When oil is passed through the fuller's earth column, it is then sent back to the fine filter module for removing unwanted particles. Once the particle contaminant has been removed, the oil passes to the drying and degassing module. After the complete process, oil is then pumped back into the transformer tank through the outlet hose, which ejects the oil near the top of the transformer tank [13].

In the event, the fuller's earth column get saturated, the rerouting valve on the processor can be switched so that the oil flowing to the fuller's earth module is by-passed, allowing the reactivation process to get start. The oil processor unit operates continuously, while the adsorption module operates between cycles of processing and reactivation.

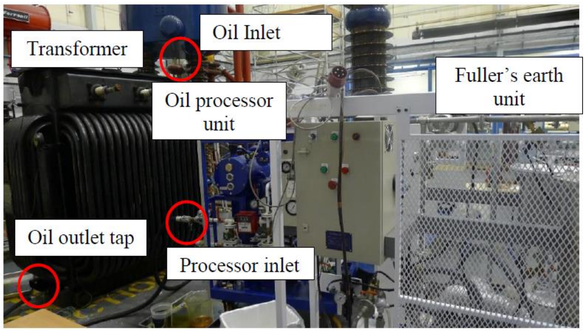

Figure 2. The experimental setup of oil reclamation process

Normally the reclamation process is repeated in many cycles to get the oil parameters as comparative to that of new oil. Commonly, in various researches it is aimed to improve the oil parameters. But we have to extent our research work by adding the effect of oil reclamation on entire insulation system coil and paper) land to compare the life span of transformer filled with reclaimed oil to the transformer in which the aged oil has been replaced with new oil. Thus our entire research work was carried out in two phase.

a) PHASE 1

The "phase-1" was aimed to improve the transformer insulation system as specified in "IEC-60296". The research work was focused to restore the oil parameters by reclamation process and its effect on the paper insulation.

b) PHASE 2

The main aim of "phase-2" is to compare the life span of transformed with reclaimed oil to that filled with new oil after aging.

III. Results and Discussions

The total capacity of liquid insulation (oil) in the tank of transformer was measured to be 300L approximately. The volume flow-rate of oil was adjusted to 150 L/h, thus it would take about 2 hours for the entire volume of oil to pass through reclamation unit. The experiment was carried out for 144 hours, so 72 cycles of oil though reclamation unit were carried out to complete the oil reclamation process (Table I).The temperature of oil was measured and monitored through the temperature sensors installed inside the transformer during sampling stage. It was recommended to operate the reclamation experiment at 70°C. The limit and profile of oil temperature was strictly monitored and controlled though out the entire process.

TABLE I. Experimental profile of Oil Reclamation process

Total volume of oil in transformer tank	300L
Flow rate of oil through reclamation unit	150L/h
Time required for entire volume of oil to pass through reclamation unit	300L / 150L/h= 2h
Number of working hours of reclamation unit	144h
Number of cycles of oil during 144 hours	144h/2h= 72 Cycles

IV. Oil Parameters

A. Acidity Number (AN)

Acidity number (AN) is the amount of potassium hydroxide (KOH) in milligrams (mg) which is required to neutralize the acidity of 1 gram of oil. The AN of new oil is about 0.02mg KOH/g, which increases with the aging of oil. From the pre-experiment inspection, the AN of oil samples was measured to be 0.22 mg KOH/g. It was suggested to reduce the AN of aged oil as comparative to the new oil. It took about 144 hours (72 passes) to reduce the AN of aged oil up to 0.005 mg KOH/g, this value is much less than the AN of new oil. Small fluctuations in the graph (Fig. 3) are due to the mixing of acidity from paper into the oil.

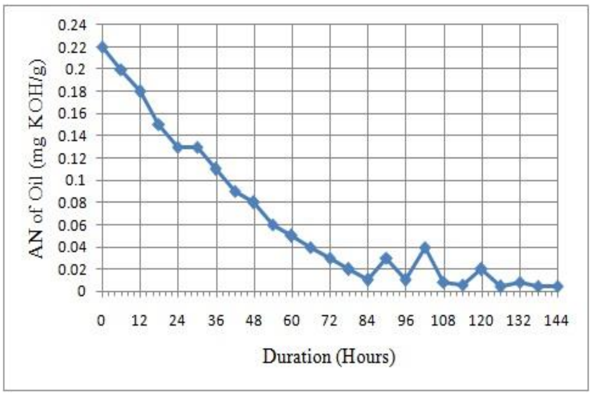

Figure 3. AN of oil duing reclamtion process

B. Moisture in oil

The presence of moisture decreases the dielectric strength of the insulating oil. The value of moisture in new oil is almost less than 10ppm, while the reclamation experiment decreases the moisture in the aged oil of transformer from 50ppm to 7 ppm, which shows the better quality of oil.

The profile of moisture during the reclamation process is given in Fig. 4. The variation in the level of moisture is due to the variation in temperature of oil in transformer tank and due to absorption of water content from the paper insulation.

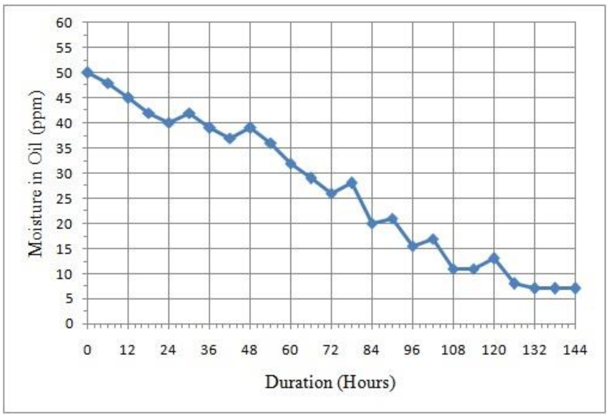

Figure 4. Moisture in oil duing reclamtion process

C. *Breakdown strength of oil*

The breakdown strength of oil is the amount of voltage in kV at which the insulating oil electrically breakdown. The breakdown voltage of new standard oil is about 60kv or greater. It was observed from the pre-experiment measurement that the breakdown voltage of degraded oil is approximately 13 kV which is much less than the cautionary value (25 kV for 11 kV transformers). The profile of improving process of breakdown voltage of degraded oil is given in Fig. 5.

After the 144 hours (72 passes) the breakdown voltage was achieved to be 72 kV which is much better than the breakdown voltage of new fresh oil.

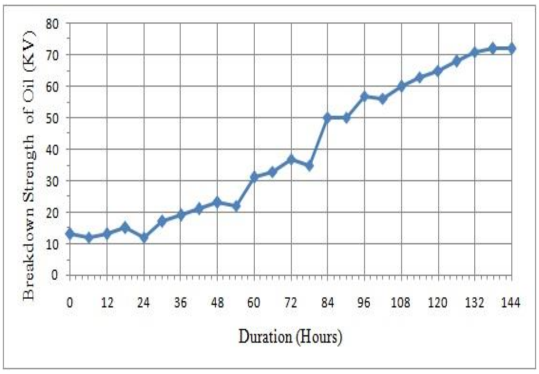

Figure 5. Breakdown Strength of oil duing reclamtion process

V. Effects of Oil Reclamation on Paper Insulation

A. *Low Molecular Weight Acidity (LMA)*

The low molecular weight acidity (LMA) of paper insulation is directly affected by AN of oil. Prior to the reclamation experiment the LMA of paper samples was measured and found to be 12 mg KOH/g on the average. After the complete 72 passes of reclamation process, the LMA of paper insulation was measured and found to be approximately 4 mg KOH/g. thus about 67% decrease in LMA of paper insulation was achieved.

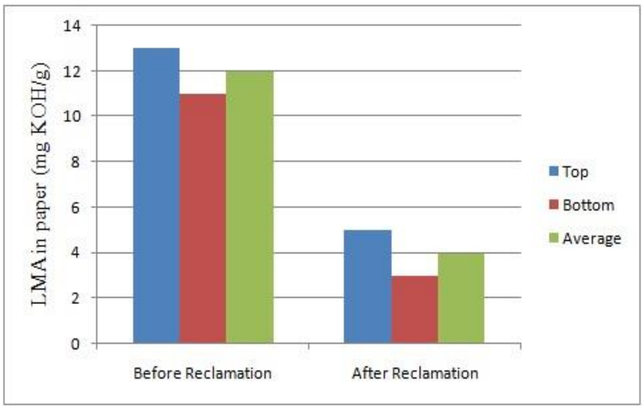

Figure 6. LMA in paper before and after the oil reclamation experiment

B. *Moisture in paper*

The moisture in paper insulation of transformer is about 99% as compared to moisture level of oil. This is the main bulk of moisture stored in paper insulation which mainly causes the failure of transformer. By inspecting the paper samples collected from the bottom and top of transformer oil, the value of moisture was obtained to be nearly 3.5 % on the average. After the complete reclamation experiment (72 passes), the paper samples from top and bottom of windings are collected again for measurement which give value of about 1.2% on the average. Thus a decrease of about 65.7% in the moisture was recorded.

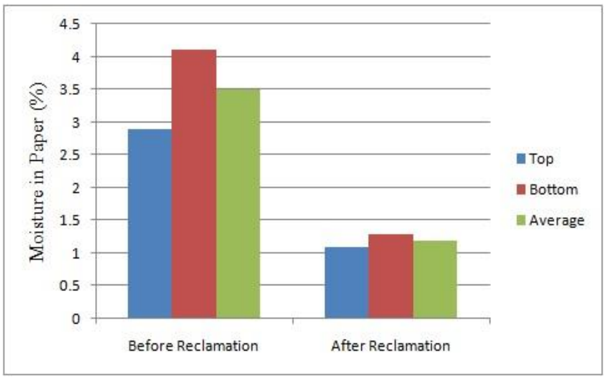

Figure 7. Moisture in paper before and after the oil reclamation experiment

C. *Degree of polymerization of paper (DP)*

The DP of paper insulation was measured for paper samples collected from different positions before and after the reclamation process. It is clear from the Fig. 8 that the increased temperature of oil for regeneration process has no noticeable effect on paper insulation.

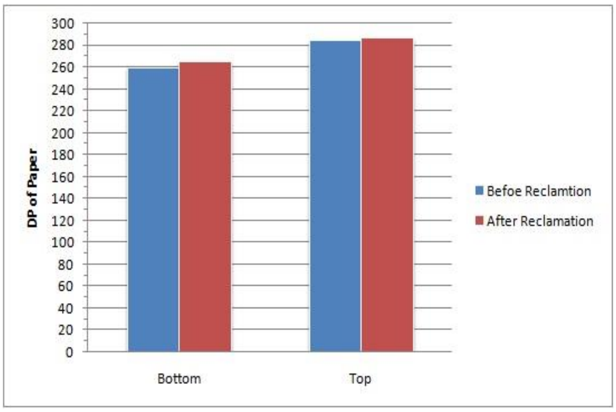

Figure 8. DP of paper before and after the oil reclamation experiment

Conclusions

This thesis is mainly aimed to improve and extend the service life of transformer by inhibiting the oil degradation through oil reclamation process. The experimented work was carried out on a 45years old, 200 KVA, 11 KV/415V-240V distribution transformers.

The entire research work was performed into two phases (phase 1 and phase 2). The "phase 1" was aimed to improve and restore the oil parameter as that of new oil and its effect on the paper insulation. "Phase 2" was aimed to compare the life span of the reclaimed oil filled transformer with the transformer in which aged oil has been replaced by new oil.

Effective study of oil reclamation was analyzed through laboratory accelerated aging experiment and real time application on a 45years old transformer. Through the regular monitoring and measurement of oil parameters (AN, moisture and BD strength) over 144 hours and paper parameters (LMA, moisture and DP) at specific stages of phase-1, it was observed that the transformer oil-paper insulation system was significantly improved as given in Table II and Table III.

TABLE II. IMPROVEMENT OF OIL PARAMETERS THROUGH RECLAMATION PROCESS

Oil Parameters	Before Reclamation	After Reclamation	Improvement
AN (mgKOH/g)	0.22	0.005	97.7%
Moisture (ppm)	50	7	86.0%
BD Strength (kV)	13	72	81.9%

TABLE III. IMPROVEMENT OF PAPER PARAMETERS THROUGH RECLAMATION PROCESS

Paper Parameters	Before Reclamation (Average value)	After Reclamation (Average value)	Improvement
LMA (mg KOH/g)	12	4	66.6%
Moisture (ppm, %)	3.5	1.2	65.7%

"Phase 2" of the research work is aimed to compare the efficiency of new oil replaced in the aged transformer. "IEC 60422; 2013- minerals insulating oils in electrical equipment supervision and maintenance guidance" give guidance on oil condition, is given in Table IV.

TABLE IV. GUIDANCE OF OIL PARAMETERS ACCORDING TO IEC 60422; 2013

Oil Parameters	New Oil	Cautionary
Breakdown strength (kV)	60	<30
Acidity number (mg KOH/g)	0.02	0.1 to 0.2
Moisture (ppm)	<10ppm	15 to 20

The "Supervision and maintenance guidance" recognizes the research which has been carried out over years. The aging profile of replaced oil was compared to the aging of reclaimed oil though laboratory accelerated aging experiment. It was observed that the aging profile of reclaimed oil is more efficient than replaced new oil in the aged transformer [7]. It is because of the stored residuals and depleting compounds in the paper and assembly of the transformer which start acting soon as transformer start operation with the replaced new oil. Such acidity; sludge and other depleting aging by product compounds are cleaned during the reclamation process, thus formation of these compounds get delayed to enhance the service life of transformer by several years (Fig. 9)

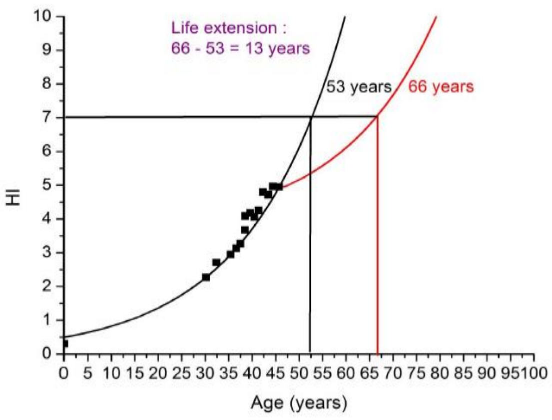

Figure 9. Estimate for improving life span of transformer

CONCLUSION/FUTURE WORK AND RECOMMENDATIONS

The investigation in this work employed equipment designed especially for indoor laboratory use, and therefore came with its own restrictions like the low speed of reclamation. Thus, there is a need to verify these findings with comprehensive industrial scale testing in order to find out the optimal oil reclamation procedure in terms of flow velocity, oil temperature and processing duration [12]. Furthermore, all the findings in this work were based on laboratory experimental work. There is a need for a model to evaluate the effect of life extension of the transformer achieved through oil reclamation. .

The ageing experiments conducted in this study utilized systems consisting of only new paper to study the performance of oil after reclamation. While these ageing experiments confirm the better performance of oil after being subject to oil reclamation procedure, they can be further extended utilizing systems of oil and service-aged paper. This would enable more comprehensive comparison of the long-term performance of paper when the transformer is subject to oil reclamation process, and aid in a more accurate estimation of life extension achieved through the procedure.

With substantial proof of the positive outcome of oil reclamation on improving the oil and paper insulation, the essential step would be to test the long-term performance of this intervention technique on an in-service transformer. Regular monitoring of the oil parameters for a period of time post-oil reclamation can confirm the long term effects of oil reclamation on the ageing rate of the transformer. These studies can also be carried out alongside similar transformers which have not been subject to oil reclamation and those which have undergone oil replacement, in order to enable comparison.

Ageing models proposed in the past rely upon the paper condition to guess the remnant life span of the transformer. However, these models solely incorporate the level of moisture and DP of paper as the indication of the ageing state. Recently, the effect of LMA on the ageing of paper insulation system was proposed. Thus, there is a need to quantify the impact of LMA on paper ageing and incorporate it in the aging model.

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