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ANALYSIS ON DEGRADATION AND DEFORMATION OF TRANSFORMER INSULATION SYSTEM

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Abstract- Performance of insulation system of power transformer is essential to ensure better performance of power network. Most of the power and distribution transformers in service are aged and, have experienced several thermal and electrical stresses due to varying loading conditions, in addition to ageing. The rate of degradation and hence, the useful life of the insulation system mainly depends on the variation of operational stresses. Due to the progress in insulation degradation, the dielectric strength of the insulating oil and paper over transformer winding may reach to a point such that it could not withstand any small abnormal currents and voltages. In order to maintain the quality of system operation it is necessary to keep the transformer in good condition. This needs appropriate maintenance based on reliable diagnostics. In this paper experimental results on the application of frequency response analysis (FRA) for the diagnosis of power transformers. Frequency Response of Transformer, also serves for assessing the deformation process.

Index Terms- Frequency Response Analysis (FRA), Ionization Current, Transformer Insulation, Weibull Distribution.

I. INTRODUCTION

The insulation system of power transformers and other electrical equipment as well is mainly constituted by mineral oil as liquid insulation and cellulose paper as solid insulation. Many of these power transformers in electric utilities around the world are approaching the end of their design life. Insulation degradation therefore becomes a major concern for these aged transformers.

Also when a transformer is subjected to high through fault currents, the mechanical structure and windings are subjected to severe mechanical stresses causing winding movement and deformations. It may also result in insulation damage and turn-to-turn faults are most likely. The deformation can also be due to ageing of paper. Deformation results in relative changes to the internal inductance and capacitance of the winding. These changes can be detected externally by FRA method. To make predictions about the lifetime of transformer insulation, it is necessary to obtain information about the Degradation and Deformation process.

In this paper an attempt have made to analyse the effect of ionisation current before and after thermal stress which shows the degradation part of insulation, identification of fault location using FRA which shows the deformation part and also mathematical analysis done using Weibull Distribution.

II. EXPERIMENTAL PROCEDURE FOR DEGRADATION OF INSULATION SYSTEM

In this paper, the analysis on the dielectric strength will be carried out on the aged transformer oil, partially aged transformer oil and new transformer oil

by subjecting it under different levels of electrical stresses for different period of time. After subjecting the oil samples under electrical stresses, the reduction in the breakdown strength and increase in ionization current of the insulating oil will be observed.

For this the following cases are used for justification, 1. Effect of Electrical Stress on Insulating Liquids for Point – Plane Electrode Configuration.

The transformer oil from various transformers in service has been taken for the investigation. The investigation mainly focuses on applying electrical stress to the oil in order to ascertain the variation of ionization current with respect to time with constant applied voltage across the electrodes. The electrode configuration involves a point – plane configuration as it is capable of providing extremely non-uniform fields.

2.1 Test cell designed for testing purpose

Aged samples and a new sample were subjected to various levels of electrical stresses which include 10 kV, 12.5 kV and 15 kV for the time period of 6 hours. During the application of voltages, the instantaneous value of ionization current has been measured every 30 minutes. Also, the measurement is obtained as

current oscillation through a digital storage oscilloscope.

2. Effect of Electrical Stress on Insulating Liquids for Plane – Plane Electrode Configuration.

The effect of electrical stress has been analysed with plane – plane electrode configuration. In this case, few aged oil samples and a new oil sample are subjected to stress conditions individually for 6 hours at the voltage level of 10 kV, 12kV and 15kV.

2.2 Test cell designed for testing purpose

For each voltage level, for the entire 6 hour duration, the conduction current through the insulating medium is measured as current oscillations through digital storage oscilloscope.

3a. Effect of Electrical Stress on Insulating Liquids after thermal stress by sinusoidal current.

2.3 Thermal stress in oil using sinusoidal currents

The above shown circuit is transformer short circuit test, which is used to generate a sinusoidal current across the secondary of transformer. The secondary of transformer was connected with the heater coil and it is immersed in a tank which consists of insulating oil. Initially Break down Voltage for each sample was noted down.

3b. Effect of Electrical Stress on Insulating Liquids after thermal stress by non-sinusoidal current.

2.4 Thermal stress in oil using non-sinusoidal currents

The above shown circuit is used to generate a non-sinusoidal current across load terminals. Here non-sinusoidal current is to be maintained constant in the heater coil. Due to this there is an increase the temperature of insulating oil, which was monitored and noted for every 5 minutes for a total period of 30 minutes.

4. Effect of Electrical Stress on Insulating Liquids before and after thermal stress for Point – Plane Electrode Configuration.

This investigation mainly focuses on applying electrical stress to the oil in order to ascertain the variation of ionization current with respect to time with constant applied voltage across the electrodes. Few aged samples and a new sample were subjected to electrical stress for the fixed time period.

During the application of voltages, the instantaneous value of ionization current has been measured every instant.

Picture 2.5 Experimental setup for Thermal Stress

After completion of electrical stress the same oil is subjected to thermal stress using the transformer short circuit test shown above in picture 2.5. By applying constant amount of current across heater coil for a period of 30 minutes and temperature was noted for every 5 minutes.

After completion of thermal stress the same oil is subjected under electrical stress for the same time period.

5. Effect of Electrical Stress on Solid Insulation before and after thermal stress for Point – Plane Electrode Configuration.

This work consists of an impregnated pressboard disc held between point-plane electrodes. Discharges data are recorded according to their phase of occurrence with respect to the power frequency cycle, their magnitude and number over a period of time.

This evaluation consists of two steps,

- Analysis on the effect of electrical stresses on insulating pressboard immersed in different transformer oils before thermal stress.

- Analysis on the effect of electrical stresses on insulating pressboard immersed in different transformer oils after thermal stress.

Picture 2.6 Pressboard in between point-plane electrode configuration

III. EXPERIMENTAL PROCEDURE FOR DEFORMATION OF INSULATION SYSTEM

In this paper, the deformation of insulation system analysis is carried out by Frequency Response Analysis technique.

There are two types in which Frequency Response Analysis can be carried out,

- By injecting various discrete frequency signals in to the winding (DFRA).
- By injecting an impulse into the winding (IFRA).

1. Discrete Frequency Response Analysis (DFRA).

A Discrete Frequency Response Analysis (DFRA) was conducted on 1KVA single phase transformer (230V/230V) and 315 KVA three phase transformer (11 KV/433V).

3.1 Layout of the Transformer Tapping Arrangement

Here the frequency signal was injected at one terminal (1U) of the HV winding while all the other terminals of the HV winding were shorted and earthed. The low voltage winding terminals 2U, 2V, 2W and the neutral were shorted and earthed as well.

- The different faults were simulated by short circuiting the transformer tapping of one of the windings in different ways. The cases considered were 50 %, 37.5%, 25% and 12.5% short.
- The frequencies at which the test was conducted were around 50 frequencies from 20Hz to 500 KHz. The frequency was varied using frequency generator.

2. Impulse Frequency Response Analysis (IFRA).

3.2 Test Set Up For Performing IFRA

The above figure shows the single stage Impulse Voltage Generator set up. The HV winding of the three phase transformer is of disc type with at total of 8 discs per phase (12. 5% winding per disc). The transformer is connected to the Lightning Impulse set up at 1U. 1V and 1W are the other HV side terminals. Similarly 2U, 2V, 2W and 2N are the terminals of the LV side. A 245Ω resistance parallel with another 245Ω resistance is placed in series with transformer winding for the sake of current measurement.

IV. RESULTS AND DISCUSSION FOR DEFORMATION OF INSULATION SYSTEM

1. Effect of Electrical Stress on Insulating Liquids for Point – Plane Electrode Configuration.

From the observation, it is evident that the trend of current variation is increasing as time progresses.

4. 1 Ionization current– time plot for an aged transformer oil

It is also observed that the formation of localized high field intensity region across the gap is very certain for a specific period of time during the constant application of electrical stress.

4.2 Variation of ionization current for a constant electrical stress

This localized high field intensity region is identified by sudden raise in the current trend reaching very high value of current and after a period of time the increase in the current reduces to a normal value as shown in the Digital Storage Oscilloscope.

2. Effect of Electrical Stress on Insulating Liquids for Plane – Plane Electrode Configuration.

When compared with the previous point - plane electrode, there is no drastic variation in the current trend but it clearly shows the variation is non-monotonous and the current through the medium gradually rises right from the initial hours and showed consistently an increasing trend for all the oil samples. Also, in the present case, the increase in conduction current is only during the initial arcing periods.

4.3 Ionization current– time plot for aged transformer oil

The breakdown strength of the oil was also measured before and after the stress conditions and found there is a decrease in the Break down voltage value.

3. Effect of Electrical Stress on Insulating Liquids after thermal stress by sinusoidal and non-sinusoidal current.

There is an increase the temperature of insulating oil and viscosity of oil gets reduced compared to the oil before applying sinusoidal currents, which was monitored and noted for every five minutes for a total period of thirty minutes.

4.4 Temperature– time plot for transformer oil

4.5 Breakdown Voltage VS Sine and Square wave plot for transformer oil

But comparatively in non-sinusoidal current the increase in temperature is greater than sinusoidal

currents, also the viscosity of oil gets reduced much compared to sinusoidal currents due to the harmonics present in inverter circuit. Then again BDV was measured.

4. Effect of Electrical Stress on Insulating Liquids before and after thermal stress for Point – Plane Electrode Configuration

In this positive half cycle was divided into 12 equal phase windows ($\phi 1$ to $\phi 12$) and partial discharge magnitude distribution in each phase was determined.

4.6 Ionization current during initial stage of electrical stress before thermal stress

From the results obtained from electrical stress before thermal stress shows that two phases ($\phi 5$ and $\phi 7$) near the vicinity of the positive voltage peak were found to contribute significantly to the aging process of insulation pressboard which is immersed in transformer oil. Also from the waveforms we can understand that the base value of ionization current and the magnitude of the pulse are not varied.

PHASE WINDOWS												
TIME	$\phi 1$	$\phi 2$	$\phi 3$	$\phi 4$	$\phi 5$	$\phi 6$	$\phi 7$	$\phi 8$	$\phi 9$	$\phi 10$	$\phi 11$	$\phi 12$
15 MINS	2.75000	1.33333	1.08333	2.75000	5.83333	3.50000	10.83330	5.33333	1.50000	3.75000	4.08333	2.33333
30 MINS	1.75000	2.25000	1.58333	4.16667	10.50000	4.25000	4.41667	7.41667	3.66667	3.58333	2.00000	1.25000
45 MINS	1.91667	1.33333	1.16667	4.41667	2.25000	6.75000	10.41670	3.83333	3.08333	3.75000	2.00000	1.91667
60 MINS	2.66667	3.08333	2.25000	2.41667	10.91670	8.91667	4.83333	5.25000	6.91667	3.41667	4.83333	2.33333
75 MINS	1.50000	2.58333	1.25000	1.08333	5.75000	3.75000	10.66670	3.33333	3.91667	3.58333	2.00000	2.66667
90 MINS	1.41667	1.91667	1.75000	5.58333	3.08333	7.00000	10.25000	2.75000	2.00000	1.33333	4.91667	3.16667
105 MINS	1.50000	2.58333	1.75000	1.08333	5.58333	6.66666	2.00000	3.08333	1.00000	4.75000	1.25000	3.41667
120 MINS	1.83333	1.00000	5.00000	1.58333	1.00000	5.16667	2.33333	10.41670	8.00000	1.25000	3.75000	1.41667

4.7 Magnitude of Conduction Current Discharges

After completion of electrical stress the same oil is subjected to thermal stress to analyse the effect of thermal stress in ionization current base value and shifting of pulse from one window to other. By applying constant amount of current across heater coil for a period of 30 minutes and temperature was noted down for every 5 minutes. After completion of thermal stress the same oil is subjected under electrical stress of 5.5 kV for the time period of 3 hours. During the application of voltages, the instantaneous value of ionization current has been measured every 15 minutes as like before and waveforms are captured in digital storage oscilloscope as shown below.

4.8 Ionization current during initial stage of electrical stress after thermal stress

From the results obtained from electrical stress after thermal stress shows that the discharge spreads to more than four phase windows (ø5 to ø8) near the vicinity of the positive voltage peak were found to contribute significantly to the aging process of insulation oil much greater than the electrical stress before thermal stress.

5. Effect of Electrical Stress on Solid Insulation before and after thermal stress for Point – Plane Electrode Configuration.

Similarly for pressboard, from the results of the analysis after thermal stress show that the discharge spreads to more than four phase windows (ø2, ø3, ø7&ø8) and also the magnitude of the ionization current increases compared to the value before thermal stress. This ionization current is contributing much greater than the previous case significantly to the aging process of insulation pressboard immersed in oil.

V. RESULTS AND DISCUSSION FOR DEFORMATION OF INSULATION SYSTEM

1. Discrete Frequency Response Analysis (DFRA).

5.1 Comparison of Reference Waveform with Different Short in Single Phase Transformer

The 5.1 graph shows the frequency verses magnitude graph of single phase transformer. In that without fault (Reference) graph was compared with all four cases (1.Short-circuit between 0-30 turn, 2.short-circuit between 30-60 turn, 3. Short-circuit between 0-60 turn and 4. Short-circuit between 60-120 turn.) are of artificial faults.

Here, we can clearly visualize the difference for same percentage faults. First and second graph from above figure 5.1 are of same percentage fault only, but there is wide variation in waveform for higher frequencies. Similarly third and fourth graph from same figure are having same percentage fault only, but here there is no major variation. So through this difference we can easily identify the location of the fault.

5.2 Comparison of Reference Waveform with Different Short in Three Phase Transformer

Here, we can clearly visualize the difference for same percentage faults. First and second graph from above figure 5.2 are of same percentage fault only, but there is wide variation in waveform for higher frequencies. Similarly third and fourth graph from same figure are having same percentage fault only, but here there is major variation in higher frequencies. So through this difference we can easily identify the location of the fault.

2. Impulse Frequency Response Analysis (IFRA).

Comparison for 12.5% short:

5.3 Comparison of Reference Waveform with Different Short Circuit in Three Phase Transformer

The above shown was a comparison of reference waveform with four different shorts. Diagnosis of faults in Transformers especially shorts within the winding with Voltage and Current waveforms alone are very difficult and can lead to misinterpretations easily. On comparing the voltage and current waveforms obtained for a particular percentage of short, with the normal condition, a few variations in waveforms are observed. However, the change in the current need not necessarily have been due to a fault, but it might just have been a result of the change in corresponding voltage. Also, on comparing the waveforms of the two different cases with the same percentage of short, it is very hard to distinguish among the two faults.

5.4 Comparison of Reference Waveform with Different Short Circuit in Three Phase Transformer

Thus observing the voltage waveform or the current waveform alone is found to be inconclusive with regard to fault detection.

VI. STATISTICAL ANALYSIS OF DEGRADATION PROCESS USING WEIBULL DISTRIBUTION.

1. Introduction:

This chapter deals with the statistical analysis of data's obtained in various cases using the Weibull distribution function, Here the failure rate of the insulating medium is predicted for a specific operating condition. The prediction of reliability is restricted to one parameter Weibull distribution.

2. Results And Discussions:

In this Paper, apart from the experiments on insulating oil samples, the outcome of the experiments was analysed using Weibull distribution. In order to ascertain the degradation rate of the transformer insulating oil for a specific operating condition, the Weibull characteristics were plotted in terms of probability density function (PDF) and cumulative distribution function (CDF) with respect to time.

TIME (MINS)	CURRENT (A)	CUMULATIVE DISTRIBUTION FUNCTION	PROBABILITY DENSITY FUNCTION
30	5.10204E-05	7.3455E-05	1.295714199
60	5.18706E-05	7.4557E-05	1.293573158
90	5.27212E-05	7.5656E-05	1.291469358
120	5.35714E-05	7.6753E-05	1.289403533
150	5.44216E-05	7.7849E-05	1.287373444
180	5.52722E-05	7.8943E-05	1.285376978
210	5.61224E-05	8.0035E-05	1.283414844
240	5.69727E-05	8.1125E-05	1.281485320
270	5.78237E-05	8.2213E-05	1.279580178
300	5.86737E-05	8.3301E-05	1.277680178
330	5.95237E-05	8.4387E-05	1.275780178
360	6.03737E-05	8.5473E-05	1.273880178

6.1 Values of Probability Density Function and Cumulative Distribution Function

The above shown table is for old sample for electrical stress of 12.5KV for a period of 6 hours.

6.2 Plot of PDF & CDF for a Fixed Scale and Shape Parameter

The above graph represents the Weibull curve for one of the aged transformer oil sample. After subjecting the sample to a particular level of electrical stress, the value of PDF and CDF is calculated based on the values of ionization current measured by performing electrical stress experiments on the oil samples.

From the observation of PDF, it is very clear that as time progresses, the value of PDF decreases appreciably. The reduction in the Probability density estimate suggests that the due to the increase in

ionization current, the dielectric property of the oil degrades and rate of degradation is taking the trend as shown in the graphical representation.

From the observation of CDF, it is very evident that the graph of CDF exactly portrays the trend of current– time plot shown in Figure 6.2. This is the proof from the two graphical representations that the use of Weibull distribution is very much justified.

VII. CONCLUSION

The results give a clear picture about the mobility of charge carriers across the electrodes. As the elementary principle of breakdown mechanism suggests, in presence of non-uniform fields, the field intensity at various points within the medium is different which makes the charge carriers to concentrate in particular location.

From the observations, it is very evident that the dielectric integrity gets affected by the temperature variations which tend to increase the partial discharges occurring internal to the oil when they were subjected to electrical stress. Increase in the intensity of discharge pulses is the vital source for the degradation process. DFRA shows that there will be a unique frequency response for a unique fault condition. Thus DFRA is capable of identifying the fault and locating the same. The DFRA and IFRA, both are non destructive and they do not cause any temporary or permanent damage to the transformers under test. They are less time consuming and free from any kind of misinterpretation.

And finally Weibull distribution is used to plot Probability Density Function, Cumulative Distributive Function which helps us to justify the degradation of insulation system.

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