PREMATURE FAILURE OF DISTRIBUTION TRANSFORMERS –A CASE STUDY

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Abstract-
Distribution transformer is an essential link in the distribution system. Failure of distribution transformers causes capital loss and loss of revenue to the nation. The premature failure rate of distribution transformers is above 25% in some of the regions of the state of Madhya Pradesh (M. P.), India. This paper presents a case study of four distribution transformers which failed within the warranty period of three years, out of which three were installed in rural areas and one in urban area. Two transformers have same specifications but are supplied by different manufacturers. It is found that the main cause of failure of distribution transformer is overloading /unbalanced loading. The results are then verified by Dissolved Gas Analysis (DGA). Transformer oil degrades due to thermal aging caused by continuous overloading. Hence, properties of oil are analyzed in failed distribution transformers. The oil samples of 27 distribution transformers of different kVA ratings, which failed within the warranty periods, were taken for this study. Breakdown voltage (BDV), Total Acid number (TAN) and Viscosity of the oil samples were measured and analyzed. The obtained results show that total acid number and viscosity increase significantly due to thermal aging and the breakdown voltage (BDV), decreases substantially. Therefore monitoring of these parameters can appreciably reduce the premature failure of distribution transformers.

Keywords -Breakdown voltage; causes of failure; cold load pickup; overloading; premature failure; thermal aging; total acid number; viscosity

I. INTRODUCTION

Distribution transformer is an imperative link of the distribution system without which the utility would not be able to supply electricity to consumers. Due to constantly increasing population and hence load demand, the number of distribution transformers is now continuously increasing. In the event of failure of distribution transformer, apart from the loss of capital to the utility, the consumer suffers due to inconvenience caused by the interruption of power supply. Power supply utility also suffers due to loss of revenue for supply outage period. In India, the failure rate of distribution transformers is very high, around 25% per annum. Statistical data indicates that over 25% failures of distribution transformers are within the warranty period of three years only and this causes an immense capital loss. In M.P., more than 300,000 distribution transformers are installed [1]. Although the number of distribution transformers is very large as compared to power transformers but the fault diagnosis of distribution transformers has not been given proper attention as they are not as expensive as power transformers. Due to their low cost, distribution transformers are removed after failure and replaced with new / repaired one without investigating the causes of failure. Therefore an investigation of the causes of failure of distribution transformer becomes essential. Here, a case study of four distribution transformers which failed within warranty period of three years is presented and causes of failure are analyzed. The diagnosis results are then verified by dissolved gas analysis. Furthermore, oil samples of 27 failed distribution transformers of different capacities are taken and Breakdown Voltage (BDV), Total Acid Number (TAN) and Viscosity are measured to find the most appropriate property that can give prior information of failure of distribution transformers and interesting results are reported.

II. THERMAL AGING

The life of a transformer is normally dependent upon the life of the insulation. As stated in the IEEE Standard C 57.91-1995 [2], transformer insulation deteriorates as a function of time and temperature. For liquid filled transformers, the traditional insulation system consists of oil and paper. Over time, the paper insulation used in transformer winding loses mechanical and electrical strength and becomes brittle when exposed to elevated operating temperature. The life of a transformer is function of its operating temperature. The term “transformer life” gives an impression as if it was quite definite, but in fact a transformer hardly ever “dies”. It is usually “killed” by some unusual stresses breaking down a weakened part leading to the end of the transformer [3]. Insulation aging is a thermo-chemical process in which aging progresses as a highly nonlinear function of the absolute temperature. Transformer temperature, in turn, is related to loading. However, the long thermal time constants of a transformer make the relationship between load and transformer temperature highly dynamic. This means that the temperature is dependent not only on the present load, but also on the loading in the previous hours. The ambient temperature adds on to the effect of loading. The winding I^2R losses, the core losses and the stray losses in the tank and metal support structures are the prime sources of heat that cause the oil and winding temperature to rise [4]. Losses in the transformer cause thermal stress in the active part. Overloading increases the current and hence increases these losses and consequently temperature of the windings and oil increases and decreases the life of the transformer. Various investigators have not agreed on life-duration at any given temperature. However, they do agree, that between 80°C to 140°C, the rate of loss of life due to aging of transformer insulation is "doubled" for every 6°C rise in temperature [3]. Thermal aging of transformer insulating material is related with the chemical reactions - pyrolysis, oxidation and hydrolysis, occurring within the transformer. They are accelerated by increased levels of temperature. This leads to aging and decomposition of both liquid and solid insulation material i.e., oil and cellulose which liberate gasses within the transformer. These gasses dissolve in the oil. The distribution of these gases can be related to the type of fault which caused the thermal stress. These faults are corona or partial discharge, thermal heating and arcing. By means of dissolved gas analysis it is possible to distinguish between the faults. The properties of oil insulations deteriorate because of thermal aging and chemical reactions. Oil ages rapidly at high temperature and moisture acts as a catalyst for its aging.

III. CASE STUDY

This paper presents four cases of distribution transformers which had a life of (1) 20 months, (2) 22 months, (3) 28 months and (4) 27 months respectively. Transformers (1) and (3) are having identical kVA rating but are supplied by different manufacturers.

(1)Transformer which failed within two years,

Its life was only one year and eight months. It was installed in a rural area. The specifications of this transformer are as follows: 100 kVA, 11/0.433 kV, DY11, 50 Hz, 3-phase, High Voltage winding current 5.25 A, Low Voltage winding current 133.33 A, aluminum wound, natural oil cooled, temperature rise 45°C, percentage impedance 4.5, quantity of oil 190 L, weight of oil 161.5 kg, weight of core and winding 280kg, total weight 598kg.

It was found by inspection that all three high voltage (HV) windings were damaged as shown in Fig.1. All three low voltage (LV) windings were also found burnt and paper insulation was damaged as shown in Fig. 2

Figure 1

Figure 2

Diagnosis Results

This could be a classic example of overheating of both low and high voltage winding. The overheating may be due to prolonged overloading. Prolonged overloading may be caused by use of inadequate size fuses. It has been observed that line operators use more than the recommended capacity fuse wires either due to lack of knowledge or just to avoid frequently replacing the fuse especially in remote rural areas. Since this transformer was installed in rural area this must have been the reason for failure. In case of prolonged overloading, the additional loss generates more heat, which affects the burning of winding insulation, causing ultimate failure of the transformer. Cold load pickup (CLP) current may also be one of the causes of its failure. CLP is a phenomenon that takes place when a distribution circuit is reenergized following an extended outage of that circuit. Usually when a distribution circuit is restored after an extended outage, the demand is more than pre-outage demand. In M.P., load shedding of 1 to 6 hours is common in rural areas. In rural areas if connection of 5 pumps is authorized, after load shedding when supply is restored, 10 pumps are operated by the farmer to finish the required irrigation i.e. the load is doubled by each farmer. Hence CLP current is many times greater than pre-outage current which causes heavy overloading of the distribution transformers. It may be assumed that due to overloading, the temperature of the oil would have reached more than 140°C and its life became less than two years [5], i.e.transformer failed within warranty period of three years. Fig. 3 has been reproduced from[5].

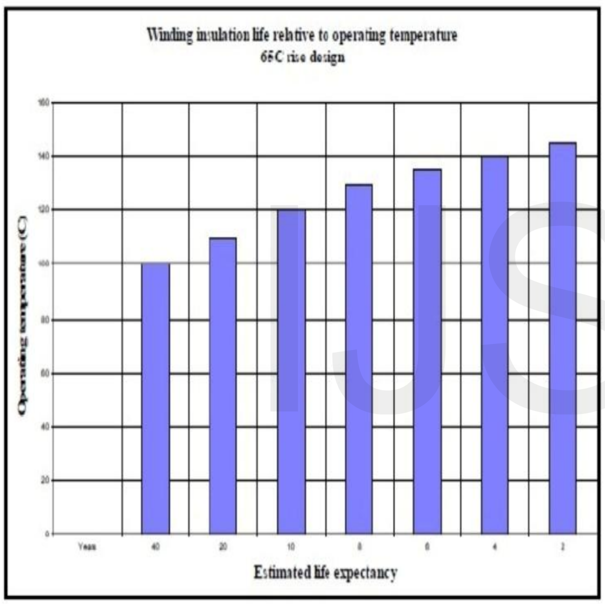

Figure 3. Transformer life expectancy vs. operating temperature

(2) ***Transformer which failed in 22 months***

Its life was also less than two years i.e. 22 months. It was installed in a rural area. The specifications of this transformer are as follows: 63 kVA, 11/0.433 kV, DY11, 50 Hz, 3-phase, High Voltage winding current 3.3 A, Low Voltage winding current 84 A, aluminum wound, natural oil cooled, temperature rise 50°C, percentage impedance 4.5, Oil 110 L, weight of oil 93kg, weight of core and winding 191 kg, total weight 382kg.

It was found by inspection that all three high voltage windings were damaged as shown in Fig. 4. Fig. 5 gives the rear view of HV windings.

Figure 4

Figure 5

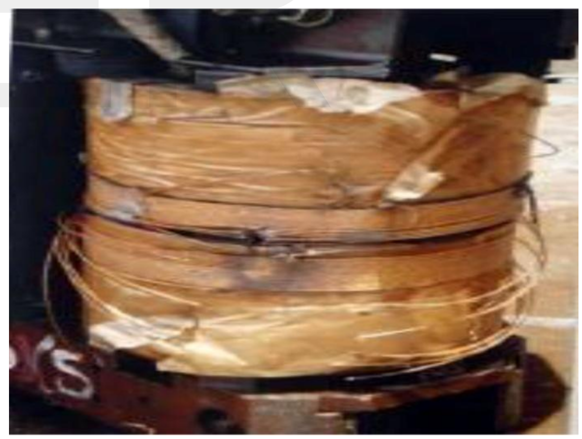

Figure 6

Figure 7

Fig.6 gives the view of R phase of HV winding in which burnout and breakage / puncture of coil can be seen clearly. Out of three windings of LV only R phase was in damaged condition, as shown in Fig. 7. Other two phases were in healthy condition

Diagnosis Results

This transformer failed due to unbalanced loading and poor maintenance. In case of unbalanced loading, voltage is generated on the neutral and will remain floating between neutral and earth. Since the neutral is solidly grounded through external link, a circulating current will flow through the loop of delta winding. This additional circulating current will superimpose on the main branch current of the delta winding and will cause additional heat, which may lead to the failure of the HV winding insulation. Proper and timely maintenance could have saved this transformer. R phase of LV winding could have burnt due to line to ground fault. In this situation, heavy current would have been drawn that cause not only the LV winding to burn but also punctured the HV winding as shown in Fig. 6.

(3) *Transformer which failed within two and half years*

Its life was only two years and four months and was installed in a rural area. The specifications of this transformer are as follows: 100 kVA, 11/0.433 kV, DY11, 50 Hz, 3-phase, High Voltage winding current 5.25 A, Low Voltage winding current 133.33 A, aluminum wound, natural oil cooled, temperature rise 50°C, percentage impedance 4.5, quantity of oil 190 L, weight of oil 167 kg, weight of core and winding 269 kg, total weight 517 kg.

It was found by inspection that all three HV windings were severely damaged. Fig. 8 gives the view of one phase of HV winding and clearly shows the burnt condition. One phase of LV windings was found in an extremely smashed condition. The remaining two phases of LV windings and paper

Figure 8

insulation were also found in severely burnt condition as shown in Fig. 9

Figure 9

Diagnosis Results

It is a case of continuous overloading as all three phases of HV and LV are utterly scorched. Sometimes all the load of a failed transformer is shifted to a nearby transformer which is already overloaded and a new transformer is not immediately available. This could have been the reason for failure of this particular transformer. The reason for severe destruction of R phase of LV winding may be the high impedance fault along with overloading. High impedance faults are often caused due to trees touching the lines. This causes continuous heavy earth fault current which may lead to failure. Since this transformer was installed in a remote rural area, routine maintenance i.e. trimming of trees might not have taken place.

(4)*Transformer which failed within two and half years*

Its life was only twenty seven months. It was installed in an urban area. The specifications of this transformer are as follows: 200 kVA, 11/0.433 kV, DY11, 50 Hz, 3-phase, High Voltage winding current 10.5A, Low Voltage winding current 266.67 A, aluminum wound, natural oil cooled, temperature rise 50°C, percentage impedance 4.5, quantity of oil 400 L, weight of oil 340 kg, weight of core and winding 455 kg, total weight 1142 kg.

It was found by inspection that all three HV windings were severely damaged. Figure 10 gives the view of HV winding and clearly shows the burnt condition. One phase of LV windings was found in burnt conditions shown in Fig.11 Remaining two phases of LV windings were in healthy condition.

Figure 10

Figure 11

Diagnosis Results

Overloading/unbalanced loading is the major cause of failure of this transformer. This overloading/unbalanced loading may be due to new connections to consumers above the capacity of the transformer or due to power theft. Often a number of new connections are added to the existing transformer without calculating the load which it can supply and line operators connect these new loads to the most reachable conductor i.e. B phase. Unequal loading in three phase causes over loading in one phase.

Use of modern electronic devices i.e. nonlinear loads, in offices, industries as well as residences is now increasing day by day due to its low cost and high efficiency. The harmonic distortion of current is increasing with the enhanced use of electronic devices such as desktop computers, laptops, uninterrupted power supplies, television, mobile phone chargers, compact fluorescent tube etc. These nonlinear loads are mostly used in urban areas. These loads draw current in the form of short pulses instead of sinusoidal wave. They draw more current than the fundamental current and cause overloading of the distribution transformer. Therefore harmonic currents produced due to nonlinear loads may also be one of the causes of its failure.

Theft of power by hooking the power line has been a regular phenomenon in both rural and urban areas. It can be assumed that power theft by some of the consumers might have been done by hooking the approachable bottom most conductor i.e. B phase of the system. This resulted into severe overloading and burning of B Phase of LV winding as shown in Fig.11.The B phase of HV winding was also overstressed by this overloading and got damaged as shown in Fig 10. Oil samples are taken from each transformer for DGA and all results are reported in Table I.

TABLE I RESULTS OF DISSOLVED GAS ANALYSIS

Component	Amount in ppm			
	Case (1)	Case (2)	Case (3)	Case (4)
Hydrogen H_2	63.281	46.451	57.464	43.92
Methane CH_4	332.76	150.608	312.767	114.76
Ethane C_2H_6	170.29	51.795	132.756	76.178
Ethylene C_2H_4	1749.487	829.082	2716.73	674.137
Acetylene C_2H_2	0.102	0.0037	0.0297	0.0215
Carbon dioooxide CO_2	2410.63	156.56	3539.12	546.44
Carbon mono-oxide CO	121.535	23.451	179.348	71.364

Results of DGA also agree with these diagnosis results as ethylene is the principal gas with some amount of ethane and methane in each case, the cause of which is overheating of the oil. Presence of carbon dioxide and carbon mono oxide indicate the paper degradation.

IV. MEASUREMENT AND ANALYSIS OF OIL PARAMETERS

Oil samples from 27 distribution transformers, which failed within the warranty period, are analysed. The voltage rating of all transformers is 11/0.4kV and the capacity ratings are 25kVA, 63kVA, 100kVA and 200kVA respectively. All transformers were installed in the state of Madhya Pradesh and supplied by different manufacturers. Experimental analysis was performed on the oil samples taken from these distribution transformers. There is no single measurement which can give a complete picture of the condition of transformer oil. There are various parameters which can be measured to assess the condition of the oil such as density, flash point, relative permittivity, breakdown voltage, dissipation factor, viscosity, specific resistance, total acid number etc. Out of these parameters dielectric strength, viscosity and total acid number of the oil were measured and analyzed. According to manufacturers in India, same oil is used in power as well as distribution transformers; therefore properties of oil from both the transformers are presumed to be same. The normal values of BDV, viscosity and TAN according to Indian standards 335 [6] are given in Table II.

TABLE II INDIAN STANDARD NORMAL VALUES

BDV	Viscocity	TAN
Above 60 kV (rms)	27cSt max at 27°C and 12 cSt at 40°C (IEC)	0.03 mgKOH/g max

A. Breakdown Voltage

Muller et al 2011 shows analysis of 37 oil samples of distribution transformers with different load histories and ages. These transformers were 10 to 55 years old and were working satisfactorily. It was found that BDV of 31 samples was above 60kV and 18 samples had BDV above 70kV as shown in Fig. 12. They were generally in a good condition regardless of their age. Mohammad R 2008 gives measurement of some parameters for nine oil samples of operating power transformers manufactured by the same company. Fig. 13 shows that all nine oil samples of operating power transformers had BDV in the range of 50 to 70kV.The aging of insulating paper and oil is studied by Shim 2010 by performing accelerated thermal aging test. Sealed aging test vessels containing copper, laminated core, Kraft paper and insulating oil were aged at 140°C for 500, 1000 and 1500 hours respectively. It has been reported that at operating temperature of 140°C, BDV was reduced from 55kV to 40kV i.e. BDV was reduced by about 30% of initial value, for aging time of 1500 hours (62.5 days only), which can be seen in Fig. 14. The test vessel does not represent the actual transformer and Fig. 14 only indicates the trend of variation. This trend is in agreement with present study of failed transformers in which BDV of all the 27 oil samples lies in the range of 12 to 46 kV, as shown in Fig. 15. This indicates that the temperature of the oil must have reached to above 140°C. Hence it may be a deciding factor for degradation of the oil due to thermal aging.

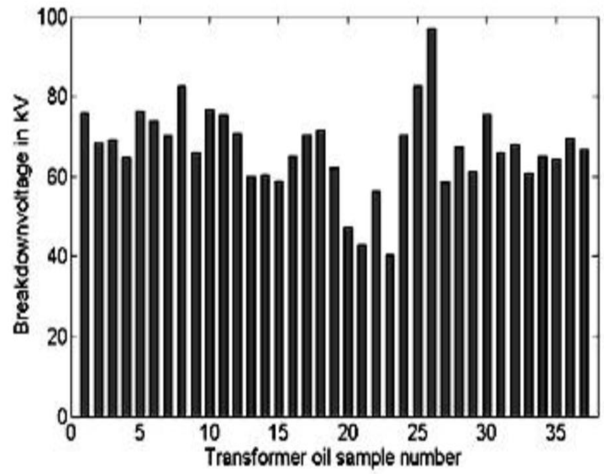

Figure 12 Transformer oil breakdown voltages in kV for each transformer oil sample [7].

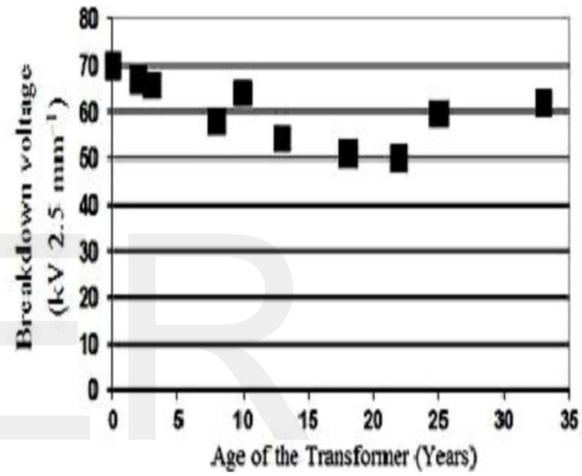

Figure 13 Breakdown voltage of the oil specimens from transformers of different ages [8]

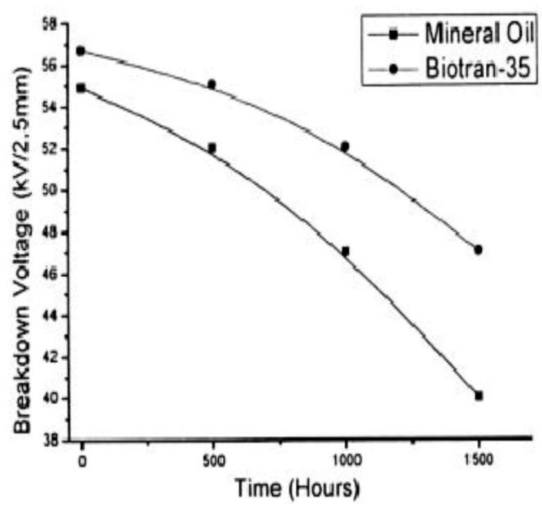

Figure 14 Breakdown voltage of two different types of oil used for insulation [10]

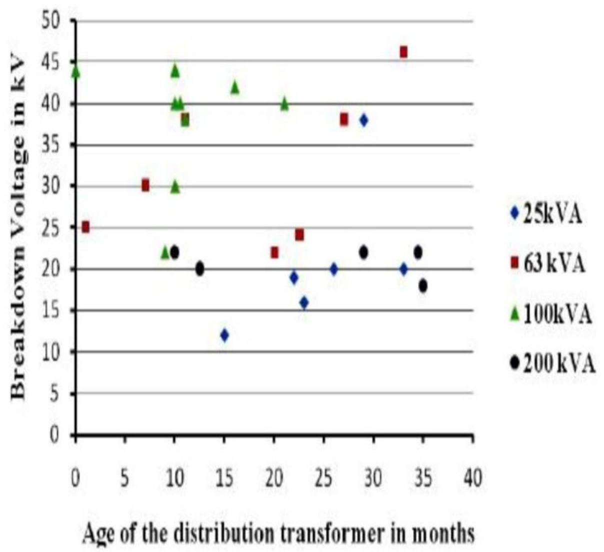

Figure 15 BDV of the oil specimens of present study

B. Viscosity

Mohammad R 2008 has reported that viscosity of all 9 samples was between 10 to 14 cSt i.e. well within the range as per IEC specifications, as shown in Fig.16 These transformers were of the age 2 to 35 years approximately and were working properly. The viscosity of transformer oil is varying from 28.09 to 65.0 cSt in the present study of 27 samples as shown in Fig.17. This high value of viscosity will result in inefficient cooling of transformer and the temperature of oil may exceed permissible limit. Hence it is a deciding factor for thermal aging of the oil.

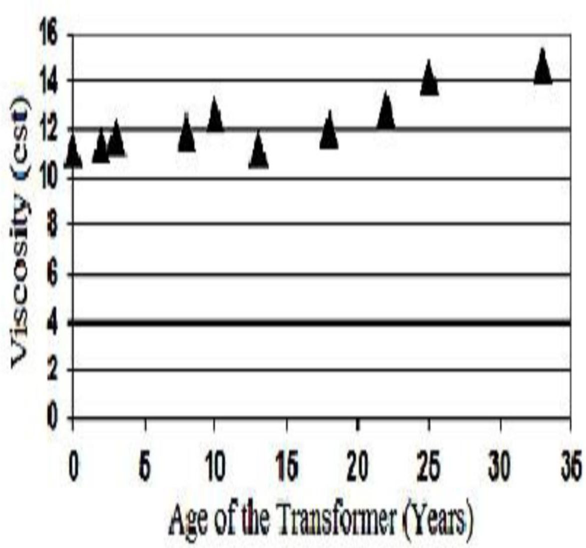

Figure 16 Viscosity of the oil specimens from transformers having different ages [8]

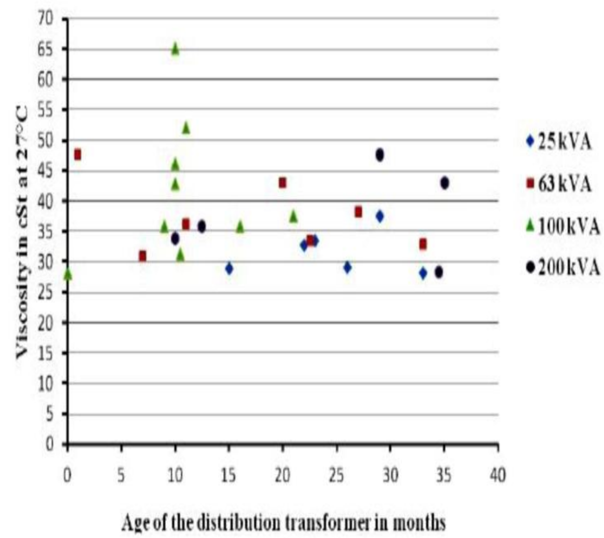

Figure 17 Viscosity of the oil specimens of present study

C. Total Acid Number

TAN is defined as the acidity of the oil which is milligrams of 0.1 normal KOH needed for neutralizing the acidity of 1 g oil. Reference [8] gives measurement of acidity of oil specimens taken from 43 working transformers of different ages (up to 29 years old). It has been reported that 20 working transformers having age up to 13 years had TAN less than 0.1 mg KOH/g oil and 18 transformers having age 14 to 25 years had TAN from 0.1 to 0.18 mg KOH/g oil i.e. 38 out of 43 transformers, having age of 1 to 25 years, had total acid number in the range of 0.06 to 0.18 mg KOH/g oil which is evident from Fig. 18. This means that up to the age of 25 years TAN remained below 0.18 mg KOH/g because transformers were not overloaded and hence not overheated.

Yoshida et al 1987 gives results of investigation of changes in characteristics of cellulose insulating materials i.e. insulating paper and pressboard, through accelerated tests using models of oil- impregnated insulating systems but these model coils do not represent the actual transformer. Fig. 19 shows the increase in acid value of insulating oil due to thermal aging in the presence of insulating paper only. It has been reported that aging of model coil for 12 months at a temperature of 140°C caused the TAN to increase from 0.002 to 0.042mg KOH/g approximately.

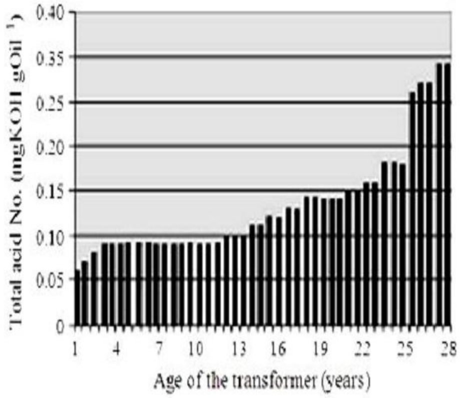

Figure 18 Acidity of the oil specimens taken from 43 power transformers of various ages [8]

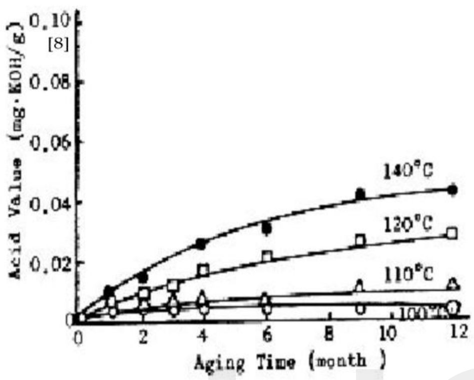

Figure 19 Increase in acid value of insulating oil due to thermal aging (Insulating paper) [9]

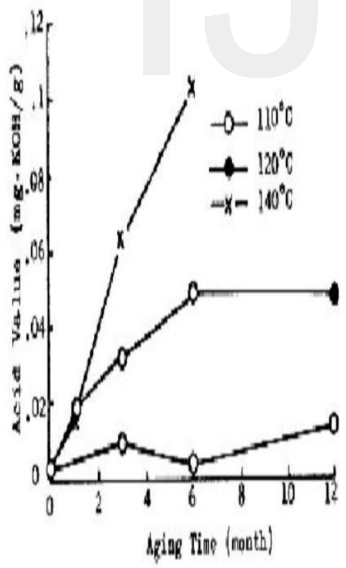

Figure 20 Increase in acid value of insulating oil due to thermal aging (Pressboard) [9].

Fig. 20 shows the increase in acid value of insulating oil due to thermal aging of model coil in the presence of pressboard only. It can be seen that a temperature of 140°C and 6 months aging caused the TAN to increase from 0.002 to 0.105 mg KOH/g approximately**.**

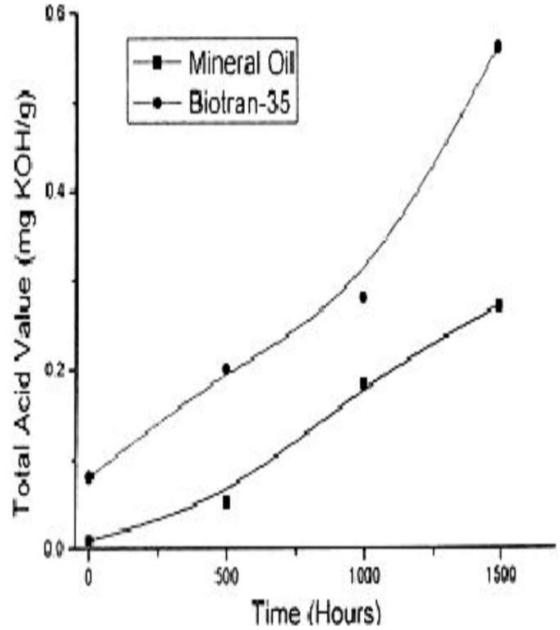

Figure 21 Total Acid Number [10]

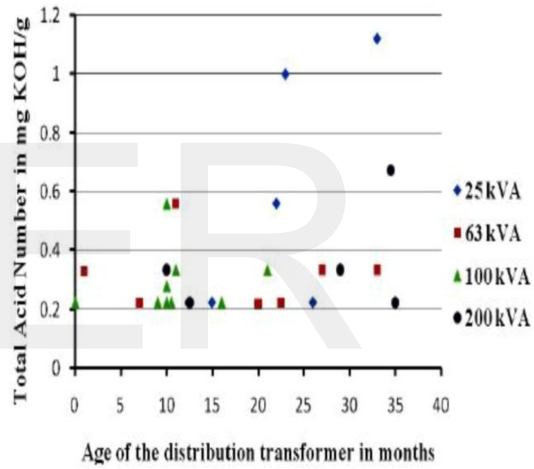

Figure 22 Total Acid Number of the oil specimens of present study

Shim 2010 simulated the distribution transformer by sealed vessels containing all materials in the same ratio as in transformer and reported that TAN for mineral oil increases from 0.01 to 0.26mg KOH/g oil at a temperature of 140°C for aging time of 1500 hours as shown in Fig. 21. This validates the results of the present study. In present investigations, it has been found that TAN of all oil samples varies from 0.224 to 1.12 mg KOH/g as shown in Fig. 22. TAN of the 21 oil samples lies between 0.224 and 0.336. This increase in TAN is due to combined thermal aging of insulating paper, pressboard and oil in actual distribution transformers.

The experiments, conducted on vessels, by Yoshida et al 1987 & Shim 2010 do not represent an actual transformer because actual windings, hot spots, core, poor workmanship etc. are not taken into consideration. The acidity measurements show that the most certain and clear change in the oil characteristics, due to thermal aging, takes place in its acidity. Hence this is the deciding factor for the life of distribution transformers as it is an irreversible phenomenon [8]. TAN does not change much over time, but at elevated temperature caused by increased load TAN increases and gives information about the accelerated thermal aging [7]. Especially for overloading and high operating temperatures over longer periods of time a rise in TAN should appear [11].

V. RESULTS AND DISCUSSION

In this paper, a case study is presented to find the causes of failure of distribution transformers which had a very short life i.e. less than three years. It is found that transformers fail mainly due to overheating caused by overloading. It is also found that the two transformers which had same rating but were supplied by different manufacturers and installed in rural area, failed due to lack of knowledge/carelessness or poor maintenance and not due to manufacturing defects for which manufacturers are blamed every time.

According to IEEE Std. 57.100, the minimum expected life of liquid-immersed distribution and power transformers, operating at 30°C average ambient, is about 20.55 years (180,000 hours) [12]. In all research work, the analyzed transformers having age more than 20.55 years, were in working condition because they operated at partial load. Hence values found for these three parameters were within the limits. Results of present study show that insulation degraded due to excessive heat and not due to normal aging. This excessive heat is caused by heavy overloading.

Causes of overloading of distribution transformer may be different for different areas i.e. rural and urban areas. In rural areas power pilferage, loading of transformer by State Electricity Boards (SEBs) personnel (without consideration of already existing load on the transformer) and CLP current are the major causes of overloading and to some extent harmonic distortion of current is responsible for failure of transformers. CLP problem occurs in rural area due to scheduled power cut in M.P. because demand is very high in comparison to generation, especially in summer. Sometimes, load shedding is done without any prior intimation to consumers and loads remain switched on during supply outage period. As soon as power is restored, all loads simultaneously draw current and overload the transformer. All distribution transformers in the state are subjected to at least one power cut everyday which may lasts for 1 to 6 hours. It ultimately causes failure of the transformer.

In urban areas most of the load is nonlinear which are increasing day by day. The increased current by each nonlinear load due to harmonics is one of the major causes of overloading of distribution transformer in the urban areas. CLP current due to loss of load diversity after a long power supply outage of 1-6 hours is another major cause of overloading. The post-outage load in urban areas may be significantly greater than pre-outage load when several, normally diverse, cyclic loads e.g. refrigerator, air conditioner etc. are all drawing current at the same time. This current is combined with the other continuously operating loads and causes the overloading of distribution transformer in the urban areas. Power theft and deliberate overloading by SEBs also leads to premature failure of distribution transformers in urban areas.

Government of Madhya Pradesh has given one point legal connections per family free of cost to all economically weak families in both rural and urban areas. This highly appreciable endeavor of the government is misused by almost 90 percent public, by drawing extra power than legally permitted, to run their appliances e.g. more number of points for illumination, fan, heater stove, electric iron, television etc., without paying for them. Cases of illegal hooking of supply lines have been reported in newspapers almost every alternate day.

During wedding season, temporary connections are provided on request in both rural and urban areas. According to a newspaper report, a temporary connection for 8kW load was requested for, in an urban area in the heart of the city. On inspection its connected load was found to be 19kW. The question that then arises is: Can the distribution transformer survive?

While installing distribution transformers, SEBs do not take into account the overloading due to reasons mentioned above and the result is frequent failure of distribution transformers within the warranty period.

VI. CONCLUSION

In India, most failures of distribution transformers occur even before the life of 3 years due to overloading. Statistics of the repairing unit considered, also show that almost 90% of transformers fail due to overheating caused by overloading. Causes of overloading of distribution transformer are different for rural and urban areas and should be taken care of accordingly. Deliberate overloading for long durations must not be encouraged. In practice, the life of a transformer can be as long as 30 years with appropriate maintenance. Two main reasons for low maintenance are: firstly, a large number of transformers are installed in remote rural areas. Secondly, shortage of skilled man power (maintenance technicians) working in SEBs. DGA is a technique widely recommended for evaluating the health of oil filled transformers. As the number of distribution transformers is very large in comparison to number of power transformers, DGA cannot be performed on each and every distribution transformer since it is an expensive method. Moreover, it requires a large quantity of oil to perform the analysis and requires expertise for interpretation of results. Tests for TAN and viscosity can be performed more easily and more frequently to assess the state of oil insulation of distribution transformers. By the measurement of TAN and viscosity it is possible to get a clear overview of the oil condition of the transformer and it can be saved from failure.

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