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Aging Study and Lifetime Estimation of Transformer Mineral Oil

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Abstract: Problem statement: Power transformer is the most expensive equipment in electrical network; and the mineral oil has the main roles of insulating and cooling in it. Oil is subjected to the degradation because of the ageing, high temperature and chemical reactions such as the oxidation. Then the oil condition has to be checked regularly and reclaimed or replaced when necessary, to avoid the sudden failure of the transformer. It will be very desirable also if we can predict the transformer oil remaining lifetime, from time to time. **Approach:** An experimental study was accomplished on the used oil specimens coming from several power transformers of various ages, working in Iranian power network, to recognize the correlation between the real age of the oil and the rate of its different characteristics and to know the most appropriate property which can represent its ageing. Accelerated aging experiments were accomplished on oil specimens at different temperatures. Furthermore a method for estimation of the remaining lifetime of the oil, using Arrhenius law, was employed. **Results:** According to our experiments, it was verified that, by using Celsius degrees and natural logarithm, the Arrhenius law can be applied properly to the thermal degradation phenomena of the oil. **Conclusion:** It was shown that the presented method can be used to study the degradation of transformer mineral oil and to estimate its remaining lifetime.

Key words: Transformer mineral oil, lifetime, degradation, arrhenius law

INTRODUCTION

The mineral oil[1-4], with the main roles of insulating and cooling in power transformers, is similar to the blood in human body. Considering the needed reliability for power transformers and the high price of the oil, we have to control the oil characteristics permanently. There are several characteristics which can be measured to assess the present condition of the oil. Using a combination of these diagnostic tests allows the oil to be monitored for changes over the time, whether the changes are due to thermal, dielectric or chemical effects. The benefit of knowing that how quickly the oil is aging, is that it allows the oil to be used as long as possible and then replacing or reclaiming it before it can cause damage to the insulating study or other materials inside the transformer.

The transformer mineral oil is one of the expensive extracts of the crude oil, produced by its refinement. Refining is the collective term for the processes involved in changing the crude oil into oil with the required properties for a particular application. Only about three percent of the crude oil is appropriate for production of transformer oil. Because of the importance of the power transformers in electrical network, permanent taking care of the oil quality is indispensable. Insulating oil in service is subjected to heat, oxygen and electrical discharge, which may lead to its degradation. This severely limits the oil to carry out its primary functions of insulating and heat transfer as aging products reduce electrical properties and cooling efficiency. Oxidation products, such as acids and sludge, are also detrimental to the solid insulation. Therefore, monitoring and maintaining oil quality is essential in ensuring the reliable operation of oil-filled electrical equipment. Even in ideal conditions, oil will degrade, as its useful service life is finite. The rate of aging is normally a function of temperature and moisture. Oil will age rapidly at high temperatures and moisture acts as a catalyst for its aging. There are also other catalysts present in a transformer that are responsible for oil degradation. These include copper, paint, varnish and oxygen. The principal mechanism of oil aging is oxidation, which results in acids and other polar compounds being formed. These oxidation products will have a deleterious effect on the study degradation processes[5]. The main oil properties are divided to the physical, chemical and electrical characteristics. Some of the more important properties

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of the oil are viscosity, specific gravity, flash point, oxidation stability, total acid number, breakdown voltage, dissipation factor, volume resistively and dielectric constant. Briefly, the mineral oil, when subjected to thermal and electrical stresses in an oxidizing atmosphere, gradually loses its stability and becomes decomposed and oxidized, its acidity increases and finally begins to produce mud. This is the degradation mechanism of the oil. In fact the aging mechanisms of oil are complicated. In general oxygen reacts with certain hydrocarbons by a free radical process, which generates hydroperoxydes. Hydro peroxides are not stable and decompose to form ketones and water. Ketones can be oxidized further to form carboxylic acids or cleaved to make aldehydes. The presence of hydroxyl groups will result in the production of alcohols and phenols. Most oxidation products will have a negative effect on the electrical properties of the oil. The carboxylic acids that are produced will either dissolve in the oil or volatilize into the headspace. Dissolved acids may cause damage to the paper and copper windings, while volatile acids corrode the top of the unit. As a result, all of the necessary conditions exist properly in a power transformer for the degradation of the oil. An important part of the oil degradation is caused by air in contact with the heated oil in the apparatus, which by oxidation results in the oil degradation. Hot cellulose is also a source of oxygen. Moisture is generated at temperature of over 80°C from deterioration of the oil and study generates moisture above 170°C. Hydrogen is generated from degradation of the oil at temperatures above 120°C and study generates hydrogen at temperatures over 140°C. Carbon monoxide and dioxide are generated significantly in the aged oil at temperatures greater than 110°C[5-7].

MATERIALS AND METHODS

To check the quality of used oil and its suitability for further use, different standards such as IEC60628, IEC60422, IEC60074, IEC60156, IEC60296, IEC60567 and IEEEstd64 are employed. The most common standard for evaluating used oil is IEC 60422. In this study, the electrical experiments and chemical tests were performed according to IEC standard.

To measure the dielectric constant (relative permittivity, ε_r), dissipation factor (loss tangent, $\tan\delta$) and specific resistance (ρ), a Tettex AG apparatus with capacitive guard ring and a BM11 type MEGGER were used. To measure the oil dissipation factor, the equipment vessel was warmed up to 90°C. The breakdown voltage test was performed by means of a Baur equipment with a 2.5 mm electrode gap.

Experimental procedure: We chose nine operating oil-immersed power transformers, from the same manufacturing company and of the same geographic zone, all of them filled with naphtenic-based mineral oil. Oil taken from these transformers plus unused oil constituted our 10 groups of specimens. The loss tangent (dissipation factor), dielectric constant, breakdown voltage, specific resistance, viscosity, flash point, acidity (neutralization number) and density of the specimens were measured; and the evolution of these characteristics, with respect to their present real age, was studied.

RESULTS

In Fig. 1-7 we can observe the variation of the oil characteristics of the oil specimens versus the real age of the concerning transformer.

As it can be seen from Fig. 1-3, oil density, flash point and permittivity do not have a great and obvious correlation with their age. So they can not be considered as good criterions to represent the oil degradation caused by ageing.

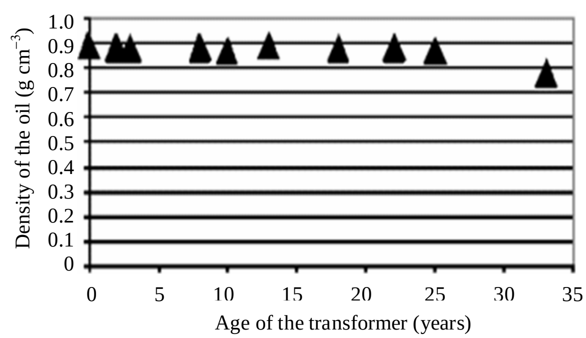

Fig. 1: Density of the oil specimens taken from transformers of various ages

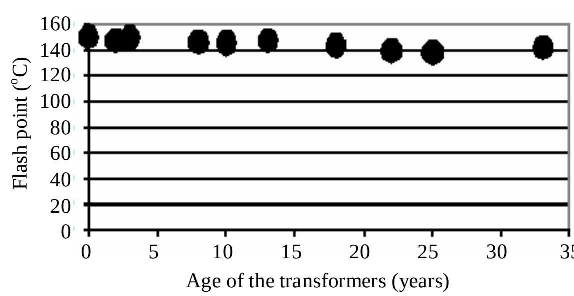

Fig. 2: Variation of flash point of the oil specimens taken from transformers of different ages

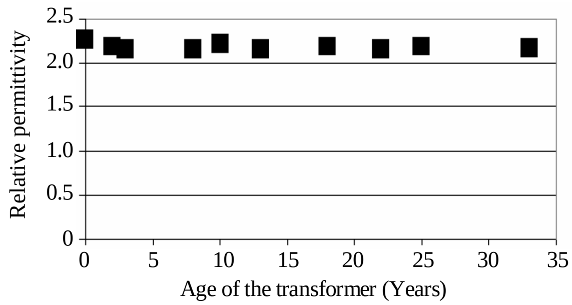

Fig. 3: Relative permittivity of the oil specimens coming from transformers of various ages

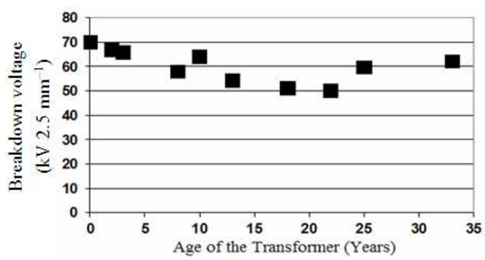

Fig. 4: Breakdown voltage of the oil specimens from transformers of different ages

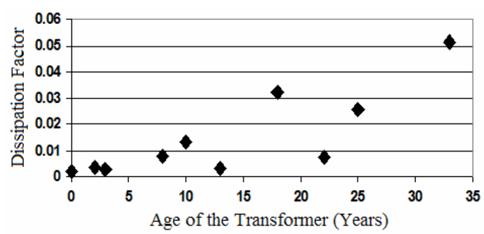

Fig. 5: Dissipation factor of the oil specimens from transformers of various ages

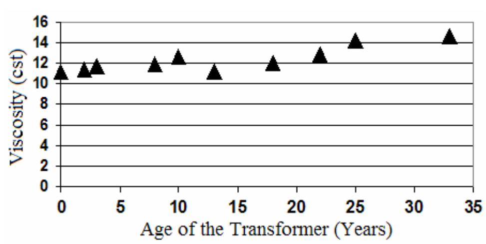

Fig. 6: Viscosity of the oil specimens from transformers of various ages

According to Fig. 4, breakdown voltage can not also represent the oil degradation. From the literature we know that this characteristic depends essentially on the water content, suspended particles and cleanliness of the oil[1,2].

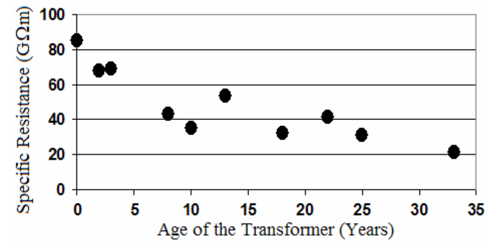

Fig. 7: Specific resistance of the oil specimens from transformers of various ages

As Fig. 5 and 6 demonstrate, dissipation factor and viscosity of the oil increase during the service time. So their evolution can be considered as an aging sign. Figure 7 shows that the oil resistivity decreases in the time and consequently its evolution can be considered too as a sign of the aging. But as we know from the literature, tan δ and resistivity also depend seriously on the oil humidity, suspended particles and dirt of oil and can change significantly by filtering and heating[7-9].

Of course by examination of the experimental results, we find that the variation of several characteristics such as the resistivity, dissipation factor, density, viscosity and flash point with the oil ageing has a logical meaning. But the acidity measurements showed that the most certain and clear change in the oil characteristics, as it ages, takes place in its acidity. A characteristic called as Total Acid Number (TAN) is defined to show the acidity of the oil. TAN is the milligrams of 0.1 normal KOH, which is needed for neutralizing the acidity of 1 g oil. The experiments showed that increasing in acidity is a certain sign of the oil degradation and no physical treatment can significantly lower it.

To have more reasonable proof for this result, acidity measurement tests were done on 43 operating power transformers of different ages, up to 29 years old. They were belonging to a company other than the owner of the nine previous transformers of the first step of the research. All of these transformers were installed in the same region.

In Fig. 8 total acidity number of the oil specimens taken from these transformers is observed. Figure 8 demonstrates a very good correlation between the real age of the oil and its acidity, which shows that the acidity can be considered as a very good criterion for the age of the oil.

Accelerated aging of the oil specimens: The Arrhenius law is a mathematical empiric law, which concerns to the influence of the temperature on velocity of the chemical reactions. According to this rule,

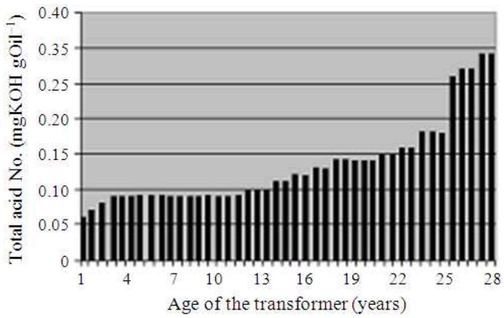

Fig. 8: Acidity of the oil specimens taken From 43 power transformers of various ages

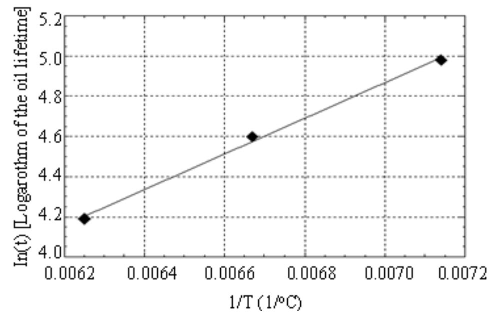

Fig. 9: Arrhenius diagram for accelerated aging an oil specimen at different temperatures

reactions are generally dependent on the temperature and the following relation can express the reaction time:

$$t = A * e^{\frac{B}{T}} \quad (1)$$

Where:

t = The time
T = The temperature
A and B = The experimental constants which are based on the reacting materials, reaction conditions and the system of units[8-9]

For example, accelerated aging tests have been accomplished on insulating study and pressboard by Montsinger during 70 weeks at the temperatures ranging from 7-110°C, by Dakin during 100 weeks at the temperatures of 100-135°C, by Shroff during 16 weeks at the temperatures of 110-140°C, by Moser during 57 weeks at the temperatures of 90-135°C and again by Moser during 3 weeks at the temperatures of 145-190°C and finally by Oomen during one week at the temperatures of 120-180°C. All these experiments have proved the validity of the Arrhenius law for the degradation phenomena of the insulating study and pressboard.

DISCUSSION

To verify the eventual validity of the Arrhenius law for the aging phenomenon of the mineral oil, we accomplished accelerated aging tests. The aging conditions were implied on oil specimens at different temperatures. The spent time at that temperature to reach the specified degradation level was noted as the specimen's lifetime. Then we plotted the logarithm of the lifetime against 1/T. Doing this procedure, if the points obtained from the experimental data on this diagram were constituting a straight line, we could conclude that this degradation phenomenon is in accordance with the Arrhenius law, because by taking logarithm from both sides of relation (1), we will have ln(t) as a linear function of 1/T. Thus, by using the extrapolation method, we shall be able to estimate the oil remaining lifetime at ordinary service temperature.

We had to be careful that the aging temperatures must be neither too separated nor too high. In other words we have to keep the aging temperatures close together as much as possible and below a certain limit to avoid a probable change in the nature of reaction. If not, data coming from the experience could not be so good to be used for extrapolation to estimate the oil remaining lifetime at its service temperature. Mineral oil is classified as a class-A insulation, whose maximum working temperature is 105°C. Then the oil aging temperature has to be high enough to keep the aging time reasonably short.

Thus we completed the accelerated aging tests on transformer oil specimens, to verify the validity of the Arrhenius law in the oil degradation phenomena. Having verified this validity, we can use this law for estimation of the remaining lifetime of our transformer oil specimens, given from different operating transformers, to predict their remaining lifetime. For this aim, we put the oil samples in closed receptacles in a temperature-regulated furnace at different temperatures and continued the aging process, measuring from time to time their characteristics, till the measured quantities passed the critical limits. We took the acidity number as the main criterion to show the degradation. The critical acidity number was assumed as 0.3 milligram KOH to neutralize one gram of oil.

The aging was accomplished at three different temperatures of 140, 150 and 160°C. As an example for the results, the oil specimens of a 230 kV, 18 years old power transformer, reached to our degradation criterion limit, the acidity number equal to 0.3 mgKOH gOil^{-1}, respectively, after 145 h at 140°C, 100 h at 150°C and 66 h at 166°C. Bringing the results on Arrhenius diagram, as shown in Fig. 9 we observed that the degradation time and the applied temperatures form three points lying on a straight line. Repeating the procedure for the specimens of different oils, it was verified that the Arrhenius law is valid for transformer oil. From the extrapolation of the straight lines, such as that of Fig. 9, we can predict the remaining lifetime of this oil specimens, at the normal working temperature of the oil in a power transformer, e.g., 80°C. If in the example of Fig. 9, plotted with Celsius degrees and the natural logarithm, we fit a straight line on the experimentally obtained points, we reach to the following relation:

$$t = 0.5374 \exp(782.9 / T) \quad (2)$$

By extrapolation of this curve, we can obtain the remaining lifetime of this used oil specimen at 60°C equal to 249,526 h, which is 28.5 years. And if this oil operates at 80°C it will reach to non-acceptable acidity limit in 9559 h, which is about one year.

CONCLUSION

In this study, an experimental research was accomplished on the used oil specimens, coming from several power transformers of various ages operating in the Iranian power network, to recognize the correlation between the age of the oil specimens and their main characteristics. This was done to know the most appropriate property, which can represent the real age of the used transformer oil. We observed that the degradation rate of the oil augments rapidly, as the temperature increases. According to the experiments, the acidity of the oil had the best correlation with the real age of the transformer. It shows that the acidity can be considered as a very good criterion to represent the age of the oil.

Furthermore a practical method for estimation of the remaining lifetime of the oil specimens, using Arrhenius law, was presented. According to our experiments, it was verified that this law can be applied to the thermal degradation of the oil, in condition that we use the Celsius degrees and natural logarithm. So the Arrhenius diagram can be used for estimating the passed age and predicting the remaining lifetime of the mineral oil specimens. We can employ this practical method easily in industrial sites to verify the transformer oil quality and to estimate its remaining lifetime.

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