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Investigation of Cooling Technique of Large Power Transformer and Life Time Behavior analysis of Transformer Insulation

[1]Manmohan Prajapati, [2]A.Pachori

[1]PG student, Department Of Electrical Engineering, Jabalpur Engineering College, Jabalpur, (MP), India
[2]Associate Professor, Department of Electrical Engineering, Jabalpur Engineering College, (MP), India

Abstract: **The paper presents the most recent results of an advance experimental research in the area of cooling and ageing processes taking place in large power transformers in oil-paper insulation. The life-time and physical chemical diagnostics of transformers as well as studies dedicated to cooling and the economic effects of cooling optimization. The experimental verification of the model is presented to detect failures leading to an increase of the water content in transformer oil proposed. It explains the effect of the transformer oil and winding temperatures on the achievement of the expected transformer lifetime. The insulation life is directly related to temperature increase of transformer winding because of insulation follows a physical relationship based on temperature expressed by the Arrhenius equation. Temperature of power transformer can be control by provide an efficient and by improving the cooling technique there for the life of transformer increase. Issues of temperature measurements and transformer cooling system control, associated with oil-forced type of transformer cooling system (OFAFWF), are discussed in detail. The paper also discusses the effect of cooling in order to have transformer residual life-time extended and its life-cycle cost minimized.**

Keywords: **Transformer lifetime, OFAFWF cooling, insulation ageing, temperature**

I. INTRODUCTION

As the electric power demand is strongly increasing in recent years because of new appliances of large power and foreseeable future in big cities, urban substation requires larger cooling capability, as well as lower noise level and good visual effects. The traditional transformer cooling technologies mainly involve natural air cooling, air forced cooling and water cooling. And the last two cooling methods are being used more widely due to the larger and larger capacity of transformers need in urban grid nowadays. However each cooling method above has its own shortcomings when used in urban power substations.

The only advantage of natural air cooling is that its cooler is cheap and no need any maintenance. Due to poor heat transfer coefficient of air, natural air cooling system results big volume and occupies massive pricy urban land. It is known that the higher cooler is assembled above the heat centre of the transformer, the better the cooling effect is. So when the natural air cooling system is applied in substation, it implies great oil height and heavy oil pressure to the oil tank, which leads to high cost of manufacturing and risk of oil leakage .

In order to get better cooling effect, forced air cooling with fans blowing the air is adopted. However, the fans have brought noise and high failure probability besides high heat transfer coefficient. Sometimes the cooler is installed underground in urban substation to depress the noise of the fans, but the limited space and isolated air in basement deteriorate the cooling effect of wind. The result leads to the need for more fans, which means higher failure probability is brought into the whole cooling system. Sometimes pumps are adopted to draw oil circulation to get better cooling effect, but pump has even poorer maintainability than fan.

The water cooling method, with the heat transfer coefficient of water achieving more than 1000W/m^2K, has much better cooling effect than air cooling. This system is used when water is as a coolant medium. The high specific heat and heat conductivity of water make it a superior cooling medium and water-cooled transformer can get by with the smallest coolers.

The cooling system is improving day by day because the critical temperature which a constructor should take into consideration when planning the cooling system of a transformer.

It should be obvious that a good maintenance schedule and regular inspections are required to keep electrical equipment in good working order, just as it would for a fine device. There is another factor working against longevity that deserves more attention than it usually gets. That factor is temperature. ANSI/IEEE standards for metal clad and metal-enclosed switchgear limit the total temperature for most bus conductors to 105 °C. This results for the maximum design ambient of 40 °C, plus the allowable temperature rise of 65 °C. Thus, the maximum continuous temperature that most insulating materials will be exposed to is 105 °C. However, if the equipment were operated on its full temperature capability continuously 24 hours per day, 365 days per year, the life expectancy of the insulation would be pretty short. If this is so, why do we see examples of electrical equipment still in service 40 years or more after it was installed? Hence the life of transformer is related to temperature limit of transformer.

II. EFFECT OF TEMPERATURE AND HUMIDITY ON THE LIFE-TIME OF TRANSFORMERS

Consider the effect of elevated temperatures on insulation. The life of insulation follows a physical relationship based on temperature, expressed by the Arrhenius† equation:

$$k = Ae\ -Ea/RT \qquad (1)$$

In this form, the equation is not terribly useful. However, if we take the natural logarithm and rearrange the terms, it becomes a generalized expression for a straight line:

$$\ln k = \ln A - (Ea/R) * (1/T) \qquad (2)$$

Since A, Ea and R are constants, this becomes a straight line with a negative slope of (Ea/R) plotted against the inverse of temperature (1/T). The practical use of this expression is from estimating the life of electrical insulation, which would be the value “k” in the Arrhenius expression. There are a wide variety of insulating materials used in switchgear equipment, but a general rule of-thumb is the age of electrical insulation is reduced by half for each rise of 10 °C in insulation average temperature. The most commonly used indicator of electrical insulation age is dielectric capability, so the Arrhenius expression becomes an indicator of dielectric life.

In the previous century, a general estimate placed the temperature limit, below which ageing of paper insulation does not occur, at 80°C. Mont singer established in 1930 that in the temperature area between 90°C and 110°C, the life of normal paper insulation is doubled with each increased 8°C.

Some other researchers found that the doubling of velocity occurs when temperature increases from between 5°C to 10°C. Consequently today the generally adopted estimate states that an increase in temperature of 6°C doubles the velocity of ageing. Based on experience and findings, the family of standards IEC 60076-x and the standard IEC 60354, which was recently renamed to IEC 60076-7, give guidance to maximum allowed temperatures of oil and windings so that, in the given climatic conditions and with the full load of a transformer, a transformer ought to reach a normal life-time of at least 30 years. But are such expectations firmly grounded? If we analyze the results of the latest research, the question is more than justified.

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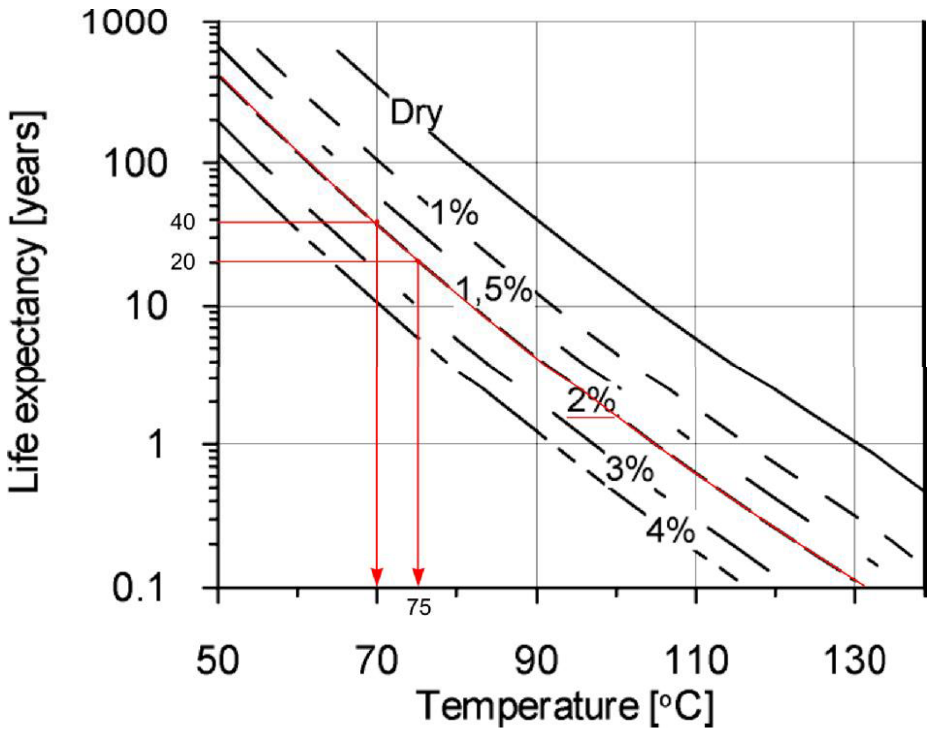

Figure 1: Dependency on temperature and humidity in the Life expectancy of paper insulation in a transformer

Figure 1 shows that the presence of humidity substantially speeds up the ageing of oil-paper insulation. Thus with temperature of a hot-spot at 98°C, a shortened life-time of 20 years could be expected in a transformer with completely dry paper throughout its life-time, however, in reality no insulation is completely dry. In an operating transformer which has on average at least 2-3% of humidity (but even can have more), for a life-time of 20 years the temperature of the hot-spot would have to be limited to 75°C. In order to reach a 40 years life-time, however, the temperature of the hotspot would have to be limited to a maximum of 70°C. The majority of humidity in a transformer is formed as a degradation product of the ageing of oil-paper insulation (normally ca 0.1% annually). Humidity, however, can also in a transformer from the air if a transformer which fails to be properly protected. We cannot prevent humidification of a transformer as the majority of humidity is formed and retained in the paper insulation of windings due to ageing processes, which again are temperature conditioned (autocatalysis). Consequently temperature, or cooling, remains practically the only method which can influence the velocity of humidification and the ageing of an operating transformer.

III. EXPERIMENTAL WORKING MODEL OF ONWFAF TRANSFORMERS

The basic purpose of a cooling system is to control the temperature of a transformer. The cooling system of a natural convection cooling system rises automatically with the rising of the temperature of a transformer. The temperature of a transformer depends on the load, atmospheric condition, cooling efficiency and ambient temperature. Power losses raise the temperature of a transformer to the point whereby an equalization of cooling power with the power losses is reached. In systems with forced convection, adjustment of the cooling power of the cooling system is carried out with the thermal device which switches oil pumps and fans on in the cooling blocks. These systems usually make use of fin type coolers whose cooling power depends on the power of fans and pumps. Since it is not always necessary to have full cooling power with partial loads and low ambient temperatures, the thermal adjusts the activity of required cooling blocks.

To verify the feasibility of applying the new cooling technology in power transformer, an experimental model is designed, implemented and tested in this paper. The heater power and the air cooling area of the model are in proportional to an oil-immersed power transformer. The model contains oil tank, electric heaters and cooling system, which is internal connected and sealed, consisting of fined tubes, condenser and linking pipes, as shown in Fig2.

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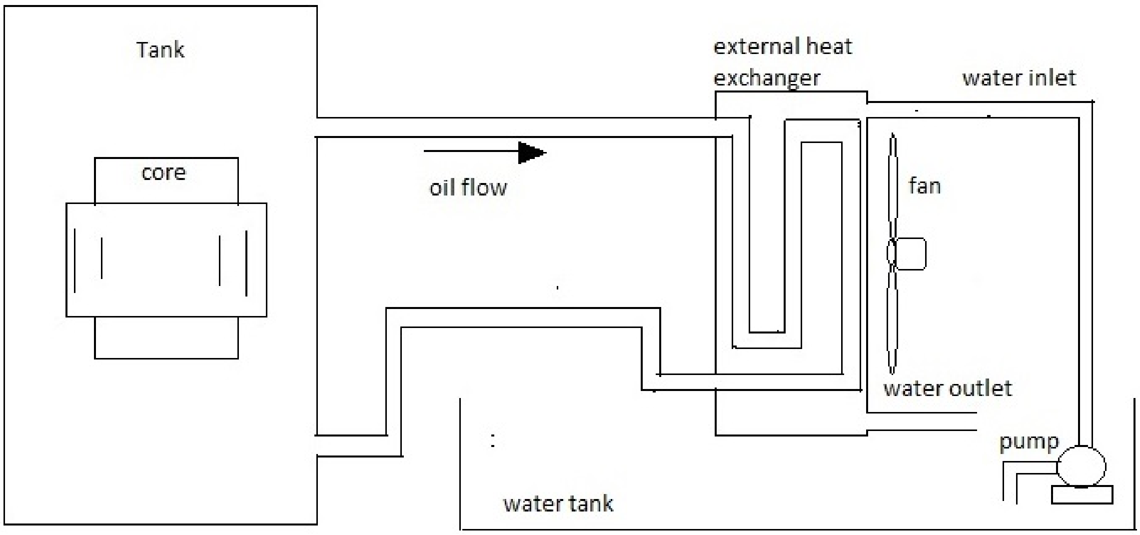

Fig2. The sketch of cooling system applied in transformer with ONWFAF

1. Cooling system parts and working:

The cooling of a transformer depends on several factors. Transformer oil must have low viscosity as possible throughout the entire working temperature interval; here we are using fresh transformer oil. A tank as shown in fig2 filled with transformer oil up to a limited volume. An electrical coil connected to the tank that increases temperature of oil. Inside the tank three sensing devices are connected at different-different height to measure the temperature of oil. These devices measure the temperature of bottom oil and top oil level and these sensing devices directly connected to electronics circuit, the circuit show the temperature of top oil and bottom oil of transformer tank, and temperature also measured by software. The electronic circuit connected with computer to USB port, the software show the temperature of every minute of transformer tank, and reading recoded by software of every second.

Fig3. Practical working model of cooling system in lab

Tank has oil pipes in which oil circulate by natural phenomena of hot oil and cold oil through these pipes oil naturally cooled.

Surround the oil pipes water circulate with the help of water pump as shown in fig2 ,water cools hot oil of tank that is flowing inside the pipes. Water filled in a water tank with a certain limed and put a pump for circulate water surround oil pipes, cold water use as a coolant for hot oil after complete the cycle hot water goes inside air forced cooling system . in air forced cooling system a fan is connected with a carburettor , now hot water comes inside the carburettor and hot water cooled by air cooling that cooled water go back to the water tank, again this process go on for maintain the temperature of hot oil.

2. Temperature range and about software:

There are three temperature sensing units which are sense the temperature of every one minute and all cooling system operate automatically at predefined temperature. Software has programmed for these temperature, it gives command to electronic circuit, in this circuit relays are connected, whenever temperature reach at predefined temperature of operation, it automatically trip and next cooling device start to cooling process.

Naturally oil cooled up to 58°C ,after 58°C water pump start it continuously cool transformer oil until temperature not reach 63 °C ,after 63°C air cooling stars. After 63°C both water pump and air cooler work until temperature not decrease predefine temperature. If temperature decrease below 63°C air cooling system automatic off, if temperature decrease below 58°C water cooling system automatically off, below 58°C oil naturally cooled only.

IV. EXPERIMENT RESULT AND DISCUSSION

Table no.1 show result of increment temperature of oil tank that is increasing in each one minute, table show only natural cooling of insulation oil of transformer tank. Temperature T1, T2, T3, are of oil tank given without any cooling system use.

TABLE-1

Water level of tank =00.0cm

Atmosphere temperature = 38°C

Time (minute)	Temperature °C			Oil natural cooling	Water forced cooling	Air forced cooling
	T1	T2	T3			
11.00am	36.0°C	36.5°C	35.5°C	√	×	×
11.03am	39.5°C	47.0°C	35.5°C	√	×	×
11.06am	41.5°C	49.5°C	35.5°C	√	×	×
11.09am	44.0°C	51.5°C	35.5°C	√	×	×
11.12am	48.0°C	52.5°C	35.5°C	√	×	×
11.15am	49.5°C	55.0°C	35.5°C	√	×	×
11.18am	51.5°C	56.0°C	35.5°C	√	×	×
11.21am	54.0°C	57.0°C	35.5°C	√	×	×
11.24am	56.0°C	59.0°C	35.5°C	√	×	×
11.27am	57.5°C	60.0°C	35.5°C	√	×	×
11.30am	60.0°C	62.0°C	35.5°C	√	×	×
11.33am	63.0°C	63.0°C	35.5°C	√	×	×
11.36am	64.5°C	63.5°C	35.5°C	√	×	×
11.39am	66.0°C	63.5°C	35.5°C	√	×	×
11.42am	68.0°C	64.5°C	35.5°C	√	×	×
11.45am	70.0°C	65.0°C	35.5°C	√	×	×
11.48am	71.5°C	64.5°C	35.5°C	√	×	×
11.51am	73.5°C	65.0°C	35.5°C	√	×	×
11.54am	76.0°C	64.0°C	35.5°C	√	×	×

T1= temperature of top oil

T2= temperature of meddle level oil

T3= temperature of bottom oil

From table no.1 we can see that temperature of oil at every three minute, experiment model start at 11am at that time temperature of bottom, meddle and top 36.0°C, 36.5°C, 35.5°C respectively, after three minute at 11.03am we are seeing meddle oil temperature T2 increasing fast as compare to T1, it is because of heating coil connected at meddle, hence coil heat up meddle oil fast as compare to top oil. Heating coil increase T2 continually and T1 increase but in slow manner and make a big difference between them but after some minute the difference between them decrease, at 11.06am T1=41.5°C, T2=49.5°C the difference between T1 and T2 is 9°C and at 11.21am T1=54.0°C, T2=57.0°C now temperature difference is only 3°C, that difference decrease continually and after some minutes T1 leads T2, can see from table, at 11.36am T1=63.5°C, T2=64.5°C it is because of natural cooling of oil. It is a property of transformer oil it cools itself by natural convection method, here natural convectional flow of hot oil is utilized for cooling. In convectional circulation of oil, the hot oil flows to the upper portion of the transformer tank and the vacant place is occupied by cold oil. This hot oil which comes to upper side will dissipate heat in the atmosphere by natural conduction, convection and radiation in air and will become cold. In this way the insulation oil in the transformer tank continually circulate when the transformer put into load. As the rate of dissipation of heat in air depends upon dissipating surface of the oil tank, it is essential to increase the effective surface area of the oil tank. From these convection process the temperature make huge difference between T1 and T2, at 11.51am T1=73.5°C, T2=65°C and at 11.54am these are T1=76°C, T2=64.0°C here we can see that transformer oil work as a self coolant or natural cooling itself. From table1 can observe that natural cooling method of oil take 54 minute to reach 76°C temperature of oil.

TABLE-2

Water level of tank = 9.6cm

Atmosphere temperature = 39 °C

Time (minute)	Temperature °C			Oil natural cooling	Water forced cooling	Air forced cooling
	T1	T2	T3			
11.00am	33.5°C	33.5°C	33.5°C	√	×	×
11.03am	35.5°C	44.5°C	33.5°C	√	×	×
11.06am	39.0°C	46.0°C	33.5°C	√	×	×
11.09am	41.5°C	48.0°C	33.5°C	√	×	×
11.12am	44.0°C	48.0°C	33.5°C	√	×	×
11.15am	47.0°C	49.5°C	33.5°C	√	×	×
11.18am	48.5°C	50.0°C	33.5°C	√	×	×
11.21am	51.0°C	51.5°C	33.5°C	√	×	×
11.24am	52.5°C	51.5°C	33.5°C	√	×	×
11.27am	56.0°C	53.0°C	34.0°C	√	×	×
11.30am	57.5°C	54.0°C	33.5°C	√	×	×
11.33am	60.0°C	54.0°C	34.0°C	√	√	×
11.36am	60.5°C	54.0°C	33.5°C	√	√	×
11.39am	62.0°C	51.5°C	33.5°C	√	√	×
11.42am	62.0°C	51.5°C	33.5°C	√	√	×
11.45am	63.5°C	53.5°C	34.5°C	√	√	√
11.48am	65.5°C	53.5°C	33.5°C	√	√	√
11.51am	67.0°C	54.0°C	33.5°C	√	√	√
11.54am	68.5°C	54.0°C	34.0°C	√	√	√
11.57am	70.0°C	54.0°C	33.5°C	√	√	√
12.00	71.5°C	53.5°C	33.5°C	√	√	√
12.03pm	73.0°C	53.5°C	33.5°C	√	√	√
12.06pm	74.0°C	54.0°C	33.5°C	√	√	√
12.09pm	76.0°C	54.0°C	34.0°C	√	√	√
12.12pm	76.0°C	54.0°C	34.0°C	√	√	√

In table no.1 show the result of oil cooled by natural cooling, table no.2 show results of oil cooling with simultaneously three cooling techniques oil natural, water forced and air forced (ONWFAF). Here for cooling technique we are providing electronics circuit board that trip the cooling system at predefine temperature through relay as sensing devices. In a table no.2 all results are of another day, hence atmosphere temperature and all other temperatures are different, at 11.00am

T1=33.5°C, T2=33.5°C and T3=33.5 °C as heating coil plug in oil temperature increase and T1, T2, T3 increase as shown in table no.2 and oil try to cool itself by natural convection method. In transformer cooling model we connect personal computer, in PC software install which give command to circuit board to start a new cooling. Natural cooling process continually work until temperature not reach 58°C, we can see that from table no.2 at 11.33am temperature T1=60°C, T2=54°C here temperature T1 is greater than 58°C hence now water pump start to cooling of transformer oil, it continually cool transformer oil until temperature not reach 63°C, after 63°C air fan on, and start to cool warm water which comes after cooling the hot transformer oil. From table no.1 we can see that to reach from 58°C to 63°C it takes 6 minute only when we are not providing any cooling, but in table no.2 we can see to reach from 58°C to 63°C it takes 15 minute, it is much more than natural cooling time. Water level after complete the experiment reduced, it become 6.5cm.

In table no.1 to reach till 76°C temperature of insulation oil it takes 54 minutes, and from table no.2 we can see that when we providing water cooling and air cooling, it takes 69 minute to reach at same temperature at 76°C.

When oil is cooled by naturally temperature T1 continually increase from 36°C to 76°C and it increase also after 76°C continuously, in table no.2 we provide three cooling system to cool the transformer oil and we see in table at 76°C temperature, continually four reading of 76°C are given by software, hence it is also a stabilized temperature of system. We can see that this cooling technique is much better technique compare to natural oil cooling.

IV. CONCLUSION

To improve the life of transformer it is necessity to provide efficient cooling system like in this paper we are trying to show the three cooling system simultaneously is working. Natural oil cooling is not only sufficient cooling for power and/or large transformer. We need a new thinks to cooled a transformer here we are using water forced cooling if temperature reach 58°C then water pump on and if temperature reach at 63°C air forced cooling start . These three cooling work together to control the transformer winding temperature and to increase the life of oil-paper insulation and/or a transformer. With optimizing cooling it is possible to lower the life cycle costs (LCC) of a transformer with normal reliability of operation. The effectiveness of optimizing depends on the capacity of the cooling system, the average load factor and the age of a transformer being optimized.

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