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Effect of Moisture on Transformer: A Review

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Abstract : Transformer works at high efficiency due to absence of rotating parts. But certain parameters like losses, moisture content in circulating oil and insulation paper needs regular monitoring which otherwise would affect the performance of the device. Water also gets generated within the transformer as a by-product of aging process. Moisture content affects life of the device, reduces dielectric strength and compromises loading capacity. So, it is very important to monitor and evaluate moisture content in the transformer. This paper presents a review of transformer insulation, moisture mechanism, effects of moisture and moisture management in transformers.

***IndexTerms* - Efficiency, Circulating Oil, Insulation paper, Moisture content, Transformer.**

I. Introduction

Transformers are static devices. Due to absence of rotating parts, it operates at higher efficiency as compared to the rotating machines. Performance efficiency and life span of transformers is greatly affected by moisture content in it. The moisture present in circulating oil used for cooling as well insulation leads to water condensation. Thermal degradation of insulation paper also gives rise to water and thus add to the moisture content in total insulation system. The moisture present in paper covering of winding adversely affects the dielectric strength. The water content also depends on temperature variation and loading conditions in addition to ingress from external environment. So, testing of oil is periodically done to keep a track of moisture. However, evaluation of moisture content in paper is also required to assess overall impact on transformer. This paper presents a review of transformer insulation, moisture mechanism, effects of moisture and moisture management in transformers.

II. Transformer Insulation

Transformers are frequently overloaded and operated beyond their capacity. Hence overloads, environmental effects and natural aging of insulation plays a major role in performance of transformers. The life of transformers is greatly controlled by the solid insulation and the insulating oil and plays vital role in performance of transformers. Selection of proper insulation system enhances the durability and stability of transformers. The common insulators used are insulating oil, insulating paper, insulating tape, press boards and wood-based laminates etc. The insulating materials used must be compatible with the oil in transformers and must not react with the oil. Oil in transformers acts as an electrical insulation as well coolant and dissipates the heat losses. Insulating paper is used for covering the winding conductors as well flexible copper is used as leads. Pressboard is a widely used insulating material for making a variety of components used in electrical, mechanical and thermal design of transformers. The areas which require higher mechanical and lower electric strength, electrical grade laminated wood is used for making a variety of insulation components like coil clamping ring, cleat etc. Insulating tapes are used in taping, banding and core bolt insulation. Insulation gives good results when it is clean, dry, relatively void-free, and utilized within a certain temperature bandwidth.

Of the mentioned insulating materials, craft insulating paper of medium air permeability is used in condenser core of oil impregnated (OIP) bushing. Resin bond paper was first used for many years for bushings but due to the resulting partial discharge, oil impregnated paper was introduced. To reduce the contact of bushings with moisture, the condenser core impregnated with oil is covered with insulating material. The main drawback of these bushings was that high pressure developed due to any internal breakdown resulted in fire and explosions of bushings. Bushings developed from untreated crepe paper impregnated with epoxy resins were covered with porcelain or composite insulators for outdoor use. Good mechanical properties, free from the development of high pressure due to breakdowns and fire resistant were the merits of these bushings. But control and monitor of moisture ingress was required to avoid the malfunctioning of these bushings. To have very low dielectric loss factor and lowest possible partial discharge, non-hygroscopic synthetic materials are used. They restrict moisture ingress and are also cost effective. Since few years Resin Impregnated Paper (RIP) bushings are fast replacing OIP bushings. The_latest development is Resin Impregnated Synthetic (RIS) bushings is that in place of paper, synthetic fabrics are used which are non-hygroscopic in nature [1].

Bushing is an important part of a transformer. Almost 20% of the power transformer failures are related to bushings. So frequent and effective diagnostic and condition assessment for bushings is necessary. The effects like excessive stress, voltage oscillations due to lightning, frequent shunt reactor switching, and continuous high levels of harmonics reduces the life of bushings and results in its early breakdown

Regular condition-based maintenance is required as the capability of the bushing reduces, as it ages. Partial discharge in bushings initially develops cracks and leads to treeing. If this phenomenon is neglected, over time it results in internal short circuit of inner foils of condenser bushings. To avoid the damage to the bushings due to the arising stress, surge arrestors are used. Sophisticated test equipment's are used for measurement of voltage and leakage current, which when monitored, the variation in capacitance and partial discharge can be noted. Condition monitoring for bushings at regular intervals, helps to avoid the damage caused due to partial discharge, variation in capacitance and stress developed.

Proper and frequent monitoring of insulators is required to maintain the efficiency. Gases and partial discharge in oil affect the insulation. Hence oil temperature, moisture content, level of oil and gas content in oil are regularly monitored through sensors or on-line devices. This reduces the chance of local overheating and partial electric discharge. Tests to check viscosity, acidity, flash point, density, dielectric strength, dissipation factor etc of insulating oil are regularly performed. Through the results of these tests, the condition of oil in terms of its current state, aging, development of any defects and overload can be obtained.

III Moisture Mechanism

The moisture content in the transformer generally depends on the internal as well external conditions wherein 60 to 70% is contributed due environmental conditions. Paper releases moisture into oil when load on transformer increases whereas as the load decreases, paper absorbs moisture from oil. This moisture content in both oil and paper drastically affects the performance of the device. 30 to 40% damage due to moisture content is due to internal conditions like cellulose or paper decomposition where moisture is produced as a by-product [2]. In a new transformer 0.5% moisture content is acceptable [3].

a. External Sources of Moisture

The moisture content in the air entering the device is absorbed by silica gel in the breathers [4]. As the load varies, the temperature inside the transformer tank keeps changing. The oil expands at higher loads and contracts at lower loads. This affects the oil level and air pressure inside the tank. Air enters the tank when oil temperature decreases. This air is passed through silica gel in the breather which absorbs the moisture which otherwise would reduce the dielectric strength of the oil. Constant maintenance of silica gel is required to avoid degradation of oil. One of the drawbacks of breathers is that if the air is highly humid then breather fails to completely absorb the moisture from it. If there are any leaks in gaskets or tank body then air containing moisture enters through it and moisture dissolves in oil. This water content can affect the paper insulation or there are chances that water may be transferred from insulation to oil also. Hence leakages must be thoroughly checked for and sealed immediately. Also temperature needs to be monitored with respect to ppm of moisture in oil and percentage of moisture in paper insulation. These results are used to find out how wet a transformer is.

b. Internal Sources of Moisture

There may be moisture in the insulation even if a transformer is new. Transformer which is operating over long periods also contributes moisture due to ageing of insulation. Insulation ageing results in de-polymerization of insulation and gives rise to by-products like CO_2, H_2O and CO [5]. This H_2O gets absorbed in paper insulation and degrades it. Moisture content in insulation degrades it faster than any acids. Moisture distribution in transformer varies with temperature. As the temperature increases towards the top, moisture concentration is found to be more at the bottom. If this is not taken care off then transformer fails due to degradation of insulation in its bottom parts.

The moisture content in oil can be differentiated in various ways. Oil has hydrocarbon molecules. When the water molecules in the oil bond with hydrogen of hydrocarbon molecules then this moisture content in oil is termed as dissolved water. This supersaturated water mixed with oil, gives a milky appearance to oil and is called emulsified water. The relative saturation ratio specifies the actual water content in the oil to the maximum water the oil can hold under certain specific temperature [6]. More water is soluble in oil at higher temperatures. Percentage of relative saturation can be monitored online to find out the decrease in dielectric strength of oil due to water content, give information of moisture content in solid insulation. These results are independent of type of oil and period the transformer is in service. During cyclic load, the temperature variations follow the load cycle and moisture ppm demonstrates a hysteresis pattern.

IV Effects of Moisture

The moisture content in transformer mainly affects loading capability, dielectric strength and life of transformer. The pie chart in Fig 1 shows major causes of failures in transformer. As seen failure related to winding contributes the maximum of 34% followed by 26% due to the failure of tap changer, 20% bushing failure, 15% because of ageing of insulation and 5 % due to fire incidences at transformers. The instances of failure at windings in addition to loading and oil leakages include faults, electrical stress and moisture ingress which are common for tap changers and bushings also.

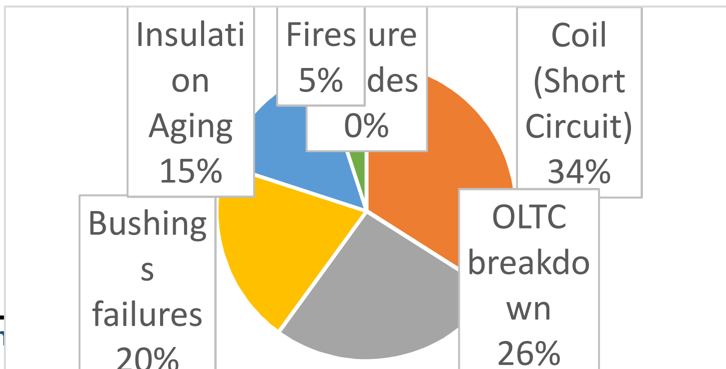

Figure 1: Component wise failure of Transformers

Excessive usage and poor maintenance of tap changers also gives rise to its failure. Pollution and improper maintenance of bushings and oil leaks also degrades performance of bushings. Insulation ageing also is the result of moisture ingress, loading and electrical stress. Moisture ingress is the common factor for all the failures in different parts of the transformer. It hence is a critical parameter in considering the long life and good performance of transformer. Considering the loading capability, it is well known that maximum operating temperature is based on the type of the insulation used. Another parameter is the winding hotspot temperature. Due to geometry of the coils, at some intricate parts the oil circulation is not that good. These parts/spots hence are not effectively cooled by the oil and they remain the hottest points in the whole transformer. These are called hot spots and temperature at these parts is called hot spot temperature. The insulation aging rate at the hot spot is the highest.

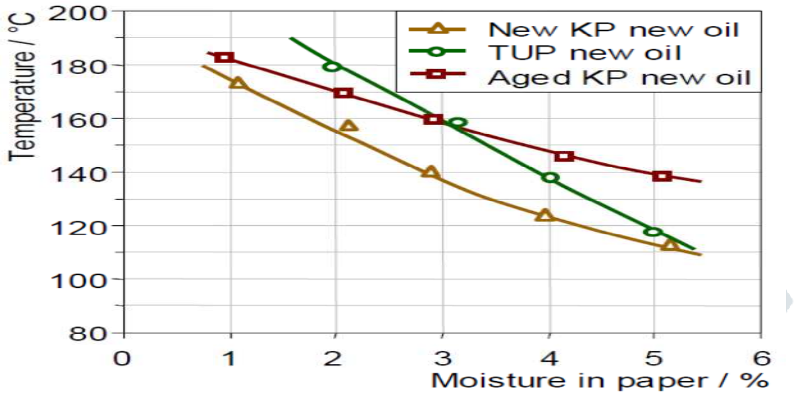

Figure 2: Hot spot temperature v/s Moisture in insulation

Fig 2[7] demonstrates the correlation between the hot spot temperature and moisture content in the insulation. Hot spot temperature varies with the moisture content and ability of the transformer to work at higher temperatures falls with high moisture content. As seen in the figure, with high moisture content of 3% the temperature is around 120 whereas same transformer can work at above 150^0C if Moisture content is 1%.

A phenomenon called bubbling largely affects the maximum allowable hot spot temperature of the transformer. The moisture in the paper gets vaporized and released in form of bubbles into the oil. The temperature at which the bubbling starts is known as “Bubbling Inception Temperature” [5]. As bubbling inception temperature depends on moisture content, in dry transformers, bubbling will start at high temperatures whereas with high moisture content, bubbling starts at much lower temperature as seen in the fig 3 [5]. If bubbling starts then vapourised water travels upward and operates the bucholz relay which causes tripping of the transformer. So if the moisture content in a transformer is low, it can be operated at high temperatures i.e with heavy loading conditions.

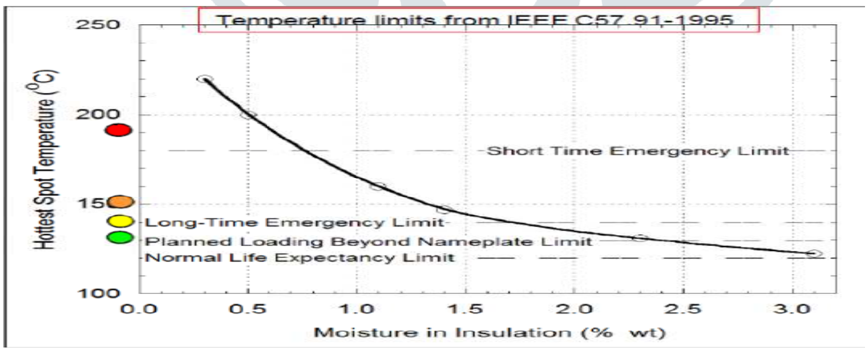

Figure 3: Correlation of Bubbling Inception Temperature and Moisture for different type of paper insulation.
KP – Kraft paper. TUP – Thermally Upgraded Kraft Paper

a. Dielectric Strength

Apart from intrinsic properties of the insulation material, dielectric strength also depends on the dryness of the insulation. The moisture affects most of the dielectric parameters of the transformer insulation. We are discussing here only its effect of partial discharges. Partial discharge is low discharge of energy in insulation. If it persists over long time, leads to treeing and eventually breaking down of insulation. When there are voids or moisture in the transformer, or power factor is low or insulation quality is not good these factors give rise to partial discharge. These discharges slowly decompose insulation and reduces its breakdown strength. Insulation fails under electric stress. The partial discharge inception voltage (PDIV) also depends on moisture. It is low under high moisture content, so discharge will start at much lower voltages. Next, the dielectric breakdown voltage of the insulation is inversely proportional to the water content (ppm). If the water concentration is maintained constant and the temperature is varied then it is noted that at low temperatures the relative saturation of the moisture is high and dielectric strength is low. If relative saturation is reduced the dielectric strength improves. So even if the oil is not totally free from moisture but its concentration is reduced from high to low, the dielectric strength of transformer can be improved. Relative strength also pays important role in performance of transformer in terms of its dielectric strength

b. Aging

Aging of insulation is mainly controlled by external moisture, electrical stress and acidity of oil. With ageing, insulation gets depolarised. It gets decomposed and gases like CO, CO_2, H_2, H_2O and chemicals called furans are released. Due to this the insulation loses its mechanical strength, ductility, tensile strength. integrity and also electrical strength. With ageing of insulation, molecular weight reduces substantially and gives rise to furans in oil. Furans in liquid insulation are developed in transformer when it is aged considerably. Concentration of furans in the oil is proportional to the percentage of de-polymerisation of paper/cellulose insulation in transformer. The furan analysis gives an idea about the remaining life of the solid insulation and consequently that of transformer [8]. Fig 4 shows results of accelerated aging test performed at 150 ^oC in Mineral Oil.

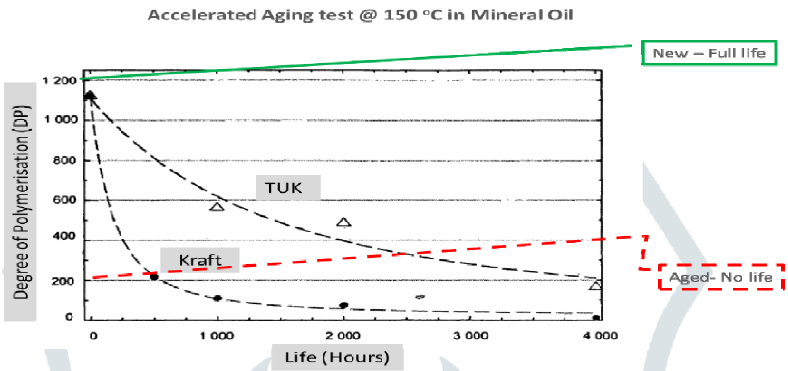

Figure 4: Accelerated aging test for Degree of Polymerisation of Insulation Paper

It shows that new insulation has high degree of polymerization (DP) and it decreases with life. At 200 DP as the insulation loses all its electrical properties, it is said to be dead. So around 300 to 400 DP the existing insulation must be replaced by a new one to avoid discontinuity of services due to further damages. Replacing paper insulation is not economical, hence transformer is replaced with a new transformer. Thus, if moisture content is controlled and periodic maintenance is carried out to maintain the dryness in transformer then the life of the transformer will increase, and it can be used for longer duration.

V Moisture Management

To avoid later effects of excessive moisture content in transformer, it can be controlled by effective monitoring and frequent measurements. Generally, moisture is monitored by performing oil testing at laboratory and also online monitoring or measurements are done. In laboratory, sample of oil is periodically taken for testing and several tests are done on the sample to find the break down voltage, water content (PPM), acidity, tan delta, capacitance, Interfacial tension, furan analysis, dissolved gas analysis etc. The results obtained from various tests helps to extract and remove the moisture before it causes any damage.
Laboratory test methods gives only ppm values of moisture in oil and does not give any idea about paper moisture. Factors like dust or humidity in the air, the container and the way in which it is transported etc may affect the end results. So online monitoring and measurements are used. Through these methods real time measurement and monitoring of moisture is achieved. Capacitive probes are used to measure relative saturation (RS) and ppm. These probes give graphical results on real time basis. But depending on the type of oil used, these probes need to be calibrated. During constant load as the oil is not free flowing, it takes time to reach equilibrium and this causes slight delay in obtaining the results of online testing. Typically, around 98% moisture remains in paper and only 2% is found in the oil [2].

a. Extraction and Removal of Moisture

Various onsite methods for extraction and removal of moisture from transformers include hot oil circulation, low frequency heating (LFH) with vacuum, vapour phase drying (VPD), On-line drying system etc. As most of the moisture is trapped in the paper insulation, it is important to break the moisture equilibrium.

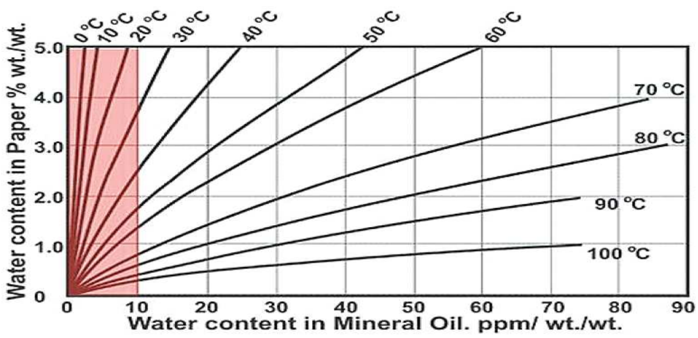

Figure 5: Moisture Equilibrium Curves

Fig 5 [9] shows various moisture equilibrium charts for different temperatures. These charts provide a quick way of estimating in-service water content of transformer insulations. It is noted that at higher temperatures, oil ppm is much lower compared to % moisture in paper and vice versa.

The first three methods are carried out off line with supply disconnected. In these methods, as transformer windings are cold the moisture equilibrium is not favorable for moisture extraction as the time required to extract moisture from solid insulation is proportional to its temperature [10]. Hot oil circulation is an old conventional method where oil is heated and circulated in the transformer. This indirectly heats the windings and paper insulation. As oil remains hotter than the windings very little moisture gets extracted from solid insulation. Another variation of this is "hot oil spray" wherein hot oil is sprayed in chamber on to the windings such that moisture molecules are released in form of vapour. The vacuum applied extracts the moisture vapour. As oil is sent back to transformer, this method is not very effective and fails to give satisfactory dryness. This drawback is overcome by low frequency heating wherein complete oil is removed from the transformer and the windings are energized by low frequency power supply to heat, it up. The vacuum is applied to suck out the moisture vapours released by the windings. To speed up the process, hot oil can also be sprayed. The vapour phase drying which is the most efficient drying method is used during the manufacturing phase of the transformer. The cost, equipment and complexity of the process limits its use. Superheated vapour of kerosene or some other suitable liquid is passed through transformer/ autoclave chamber. The vapour reaches most intricate areas of transformer, heat it and remove the trapped moisture effectively. The moist vapour later is passed through condensers where vapours, water and kerosene are separated. Water is then drained, and kerosene sent back to super heaters for re-circulation. In online drying method molecular filters are used which pass the oil and restrict the water molecules thus only moisture free oil is sent back to the transformer. This process can be carried out on a loaded transformer during normal operating condition. The windings being energised, large amount of moisture from solid insulation is released in to the oil which gets filtered out through molecular sieves. The advantages of this method are excellent drying quality and transformer need not be taken out of service. Only limitation is, being a passive system, it cannot be used for emergency drying.

VI Conclusion

Insulation is the HEART of transformer. Transformer insulation system has two components: Solid and Liquid. Among several factors moisture plays a very crucial role in performance of the transformer. Apart from moisture ingress, water gets generated within the transformer as a by-product of aging process. Moisture content in solid and liquid insulation depends upon load and temperature. Direct effect of moisture on transformer is multifold. It affects its life, reduces dielectric strength and compromises loading capacity. Indirect effect includes rusting of core, transformer body due to presence of lot of moisture in the transformer. Several methods are used to extract/ remove moisture from working transformers. The method which is able to break moisture equilibrium is the most effective one. Equilibrium has to be broken if moisture is to be removed from the paper. VPD, LFH, On-line drying are the most efficient methods to remove the moisture. LFH is the most effective and economic – off line method. Online drying is effective method to constantly remove moisture and keep the transformers dry. Any of these methods can be used depending upon the urgency and budget.

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