MAINTENANCE PRACTICES TO IMPROVE LOADING AND TO EXTEND THE LIFE OF POWER TRANSFORMERS

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SYNOPSIS

The influence of the key major factors affecting the aging of power transformers is reviewed in the paper. Suggestions are made to assess and to reduce the impact of the aging factors on the life of transformers. Life expectancy criteria are discussed. Suggestions are made to load more adequately (overload) wellmaintained units. Practical limitations to enable such loading are discussed. The benefits of the better loading on cost reduction in the expansion of power systems are focused.

INTRODUCTION

Power transformer loading and power system expansion planning are two topics usually delt by utility personnel separately from maintenance criteria. However, pertinent maintenance background information should be utilized as powerful tools to assist improving loading practices, as well as postponing investments in the construction of new substations. Such a background information refers to usual maintenance procedures performed to preserve the life of power transformers by reducing the influence of the Kraft paper aging factors.

KRAFT PAPER AGING FACTORS

It has long been a common sense among power transformer operators all over the world that their units age mainly due to the heat caused by loading. In fact, heat plays a significant role in power transformer aging, but there are some other very important factors, which also accelerate such an aging dramatically. All of these factors will be briefly reviewed to facilitate the understanding of the extent of their influence on power transformer aging and to assess the consequences they bring to life reduction.

Water is one of the most important of the contaminants that are tremendously deleterious to paper. F. M. Clark[1] stated in 1942 that the mechanical strength of a sheet of paper is reduced to the half of its initial value if its water content doubles. A practical example will facilitate the understanding of such an statement. Let’s consider that a substation has two power transformers operating in parallel at the same temperature. Now, some assumptions should be made. The first one is that the units are sisters and operate approximately at the same temperature. The second assumption concerns the water content of their solid insulation composed of Kraft paper. The water content of the solid insulation is assumed to be 0.5% for unit A and 1% for unit B. A last assumption must still be made. It refers to the expected life of unit A, which will be defined as 40 years. Based on Clark’s statement, unit B will last only 20 years. It is important to bear in mind that such a tremendous effect in life reduction was exclusively due to water. Heat contribution was not taken into consideration in this example since the operating temperatures of the two units were considered to be approximately the sarne during their whole service lives.

Oxygen is also a Kraft paper aging accelerator. In 1960, two French researchers called Fabre and Pichon[2] stated that the paper aged in open test cells in contact with air degrades 2.5 times faster than another that aged in nitrogen- or vacuum-sealed cells. In 1978, a Swedish researcher called Lampe[3] stated that a power transformer with 3,000 ppm of oxygen dissolved in the oil would last 10 times more than another with 30,000 ppm, if the two of them operated at the sarne temperature and the water content of their paper insulation was the same. Though 3,000 ppm of oxygen can usually be found in practice for nitrogen-sealed units, membrane-sealed transformers may have a higher content since oxygen permeates through the membrane very slowly. The usual maximum values reached for nitrogen-sealed units are around 5,000 ppm. For mernbrane-sealed units, around 10,000 ppm can be measured. In the case offree-breathing units, oxygen penetration would be fast and the final result can reach around 30,000 ppm.

Acids are the third accelerator of paper aging. They are formed due to insulating oil aging, but they also affect paper. In 1991, a group of Brazilian engineers headed by Siqueira[4] conducted a very interesting laboratory experiment. They dried pieces of a new Kraft paper and put them in nitrogen-sealed test tubes filled with two different oils. The tubes were aged at 155°C. A first set of tubes contained paper in contact with a brand new oil with an acid nurnber of 0.03 rng KOH/g and a water content of 17 ppm. A second set of tubes contained paper in contact with an acidic oil with an acid number of 0.35 mg KOH/g and a water content of 13 ppm. After aging, the researchers observed that the paper in contact with the acidic oil aged six times faster than did the paper aged in the new oil. The parameter established for this assessment was to reach a degree of polymerization (DP) of 200. This is considered to be a very low value, if compared with the initial value of around 1,000 usually reached after the factory drying-out process of power transformers. In such a study, ternperature, water content of paper and oxygen content of oil were practically the sarne, but the acid number of the oils was different.

Heat is the last aging accelerator of paper degradation. It has long been referred to as if its effect were almost exclusive on paper breakdown. It is widely recognized that the rate of degradation doubles for temperature increases in the range 6 – 8°C[5] Heat is inherent to power transformer operation due to losses caused by loading since one of the main reasons of any transformer is te supply the load with power. However, there are limits imposed by the unit’s design characteristics and by the need to keep operation reliability, which restrict such a power supply. For example, bubbles from dissolved gases and frorn water in the oil can evolve due to high ternperature, and this can eventually lead the unit to a failure mode. The aging rate can also be accelerated as temperature increases, rnainly if the other paper aging facters are significantly present since all of thern work sinergistically.

Maintenance practices must always be centered to rninirnize the influence of all the paper aging accelerators. Heat is an exception to this rule since it cannot be eliminated, but must be kept under control by these involved in power system operations. The water content of the Kraft paper and the oil test results such as oxygen gas centent and acid number should be kept under very strict limits. Table I shows the levels suggested as a reference. It is likely that more strict values can be suggested mainly to prevent the insulating oil aging. However, the limits presented in Table I are mainly intended to preserve Kraft paper, and the oil will also be preserved as a consequence. Stricter values are good to preserve the materiais, but an economical and technical compromise must always be searched for.

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TABLE I

SUGGESTED LIMITS TO PRESERVE KRAFT PAPER

WATER CONTENT OF KRAFT PAPER	<1%
OXYGEN GAS CONTENT OF OIL	<3000 ppm
ACID NUMBER CF OIL	<0.10 mg KOH/g

Among the imits suggested in Table I, the assessment of the water content of Kraft paper usually presents practical limitations to be obtained. A very interesting practical appreach was proposed recently by Victor Sokolov[6] which he called “water heat run test’. It consists of maintaining the oil temperature at an approximately constant value between 60 and 70°C for 72 hours. Four oil samples should be collected, one before starting the test and the three others every 24 hours. The water content of oil is measured and the final value is used as input data in a correlation plot between the water content of oil and the water content of the Kraft paper. Figure I shows a curve published by Von Guggenberg[7] in his discussien of Sokolov paper. We are presently putting the method in practice under CPFL’s power system condition. We are checking the best solutions to overcome temperature fluctuations. To prevent temperature from lowering when load decreases, we are planning to temporarily take out of service some of the fans and radiators, and put them back into service as temperature increases. Another proposal is to heat the oil by means of a degassifier if no other cheaper arrangement is feasible. Despite these possible limitations, the test has a tremendous impact in terms of assessing the Kraft paper moisture content in the field. This information is very important to establish loading possibilities and the cansequent loss of life of paper. Wet power transformers not only age faster, but they form gas bubbles at lower temperatures as compared with dry units.

LIFE EXPECTANCY BASED ON LOADING GUIDES

Loading guides state that pawer transformers with thermally upgraded insulation operating at a continuous hot-spot temperature of 110°C will last 7.42 years in service. In accord with Bill McNutt[5], G.E. and Westinghouse windings tested in EPR1-sponsored research programs gave an even better performance. The windings were aged at 180 and 200°C. After aging, the investigators concluded that the windings did not loose functionality and survived from 6.4 to 8.6 times the ANSI-defined Iife at 180°C based on lass of 50% of the original tensile strength of paper. The windings aged at 200°C gave an even better perfarmance and lasted from 12.0 to 15.3 times the reference ANSI life. Based on such an information, one can come to the following conclusions:

- The ANSI loading guide criterion for the end of life of Kraft paper is very conservative. It determines the end of life as 50% of the initial tensile strength of paper.

- The laboratory data do not match with the life observed in real world condition.

The main reasons for such a discrepancy between laboratory test results and field data are simple to understand. Laboratory tests are accelerated aging, they last no more than weeks or a few months. In the real world condition, transformer aging is very slow. It takes years or decades. Such a time span causes a tremendous practical difference. In the accelerated aging, heat is almost the exclusive degradation agent since the oil remains in a almost new condition and there is practically no oxygen penetration.

In the real world, it will be practically impassible to find a so old unit. The oil ages and becomes acidic; paper ages and forms water; the oxygen and water content of the bulk solid and liquid insulatian increases. All these agents working together with heat cause the expected long life observed in the laboratory aging tests to be dramatically reduced.

McNutt[5] propesed an update in the ANSI loading guide criteria. He suggested that the end of life were reduced to 20% of the tensile strength and were also based on a DP value of 200. The suggestion to include the DP criterion enables to put in practice the assessment of the end of life since the initial tensile strength value is hardly ever known by the power transformer operators. It is very difficult to collect a paper sample from a functional transformer to run a tensile strength test. The paper would have to present no permanent folds to enable significant test results. However, this not the case of most units. Also, the sampling location would have to be repaired and this would be labor consuming.

McNutt[5] introduced the “Transformer Insulation Life” curve relating the per unit life to conductor hot spot temperature for thermally-upgraded paper:

Per Unit Life = $9.80 \times l0^{-18} e^{15000/T}$

T = temperature in Kelvin (K = °C + 273)

The per unit life equals to 1 .0 for operation at 110°C which is the hottest-spot temperature for insulation systems with a 65°C average winding rise. In accord with McNutt’s data, it would take 158,000 hours or around 18 years for the paper located at the hottest spot of a power transformer to reach a DP of 200. The conditions established to reach such an age were that the paper operated permanently at 110°C with a water content of 0.5% and that the oil had a low oxygen content (<3,000 ppm). Though 18 years may seem to be a very short age, it is interesting to bear in mind that this temperature level is not very usual on a permanent basis. To have a more practical assessment, let’s consider a lower hettest-spot temperature at 90°C. In this case, the per unit life value obtained for 110°C would be multiplied by 8.66. After multiplying this value by 18, the calculated age would be over 156 years.

McNutt’s propesed curve is adequate for use in well-maintained power transformers. It should be used with care on poorly-maintained units. McNutt differentiates between transformers with low and high oxygen content. The calculated life for a determined hettest-spot temperature has to be divided by 2.5 for free-breathing units with high oxygen content of the oil. Another life reduction factor is suggested when the water content of paper is higher than 0.5%, the reference value. Life has to be divided by twe as the water content of paper doubles. In numbers, this means that the life of 18 years for a unit operating permanently at 110°C at the hottest spot would be significantly reduced if it were free breathing and if its paper had 1% of water content. Initially 18 years would be divided by 2 because 1% of water content is twice as much as 0.5%. The value obtained is 9 years. This value is reduced to 3.5 years after dividing 9 by 2.5 due to the high exygen content.

Though these criteria enable the use of the equation for poorly-maintained units, the acidic oil effect is not being taken into consideration. When it is not possible to know the exact values of the important equation parameters, we recommend to collect paper samples from the leads to the bushings or, preferentially, from the high voltage windings to run DP tests. The DP test results can then be used as a reference to calculate the aging the unit will undergo depending on its load in the future. However, it is convenient to maintain the paper and oil insulation in a very good condition as suggested in Table I so that heat can be almost the exclusive aging agent.

Loading guides establish a maximum daily load limit to enable the unit to reach the life expectancy determined. This causes an unnecessary load limitation. Power transformer loads change during the year. In Brazil, the maximum daily load limit is being excluded from the national loading guide criteria. Temperature monitoring systems avaliable today enable the contral of the daliy loss-of-life in a very accurate way. Traditional thermometers register only the maximum and the present temperatures. The madem temperature monitering systems can record all the important temperature fluctuations during the day. Therefore, all the significant temperature values can easily be used te caicuiate very precisely the less of life. For example, it is possible to closely moniter the extra loss-of-life caused during certain periods of time. A few months later compensation can be achieved when lead tends to be lower. These simple practical criteria make a very significant difference in terms of using more adequately the installed capacity of power transformers. Also, such an installed capacity would not be limited to the unit nameplate anymore. The limit would be given by safe maximum operating temperatures to prevent from gas bubble formation. This change of control parameters would provide a surplus in nameplate values.

The possibility to increase loading both on a daily basis and under emergency condition will enable several advantages:

1) the possibility to share the load of a failed power transformer by transformers instailed at near-by substations rather than by parallel installed transformers. The power distribution system would have to be adapted so that there were links between all substations enabling a simple and reliable load transfer on a long duration basis. In such cases, the number of low-loaded parallel units or spare units could be dramatically reduced. Investments of miilions of dollars in lowloaded or even nonloaded power transformers could be saved.

2) the possibility to increase the load factor of mest power transformers on any system to postpone investments in new units and/or substations. For example, the units could also operate with an expected overloading for a few hours daily during certain months of the year when load tends to be higher. The economical results obtained from this more aggressive loading policy are very encouraging. In the last 15 years, CPFL has increased the average loading of its power transformers.

Consequently, investments in the construction of new substations have been postponed as well as the purchase of power transformers, circuit breakers, lightning arresters, batteries etc. The savings obtained sum up to around US$ 123,000,000.00.

CONCLUSIONS

The presence of significant amounts of water, oxygen and acids in the insulating system of power transformers accelerates Kraft paper aging. Therefore, maintenance practices must be continuously implemented to keep such contaminants within economically acceptable limits. Well-maintained power transformers can be safely loaded without having an additional reduction of their expected life besides that caused by loading.

An update in life expectancy presented in loading guides was proposed by McNutt[5]. In such an update, the effects of a poor maintenance practice have been taken into consideration on the reduction of life expectancy.

In the last 15 years, CPFL has obtained very good economical results from a more aggressive loading policy of its power transformers. Investments in the construction of new substations have been postponed as well as the purchase of substation apparatuses. The savings obtained sum up to around US$ 123,000,000.00.

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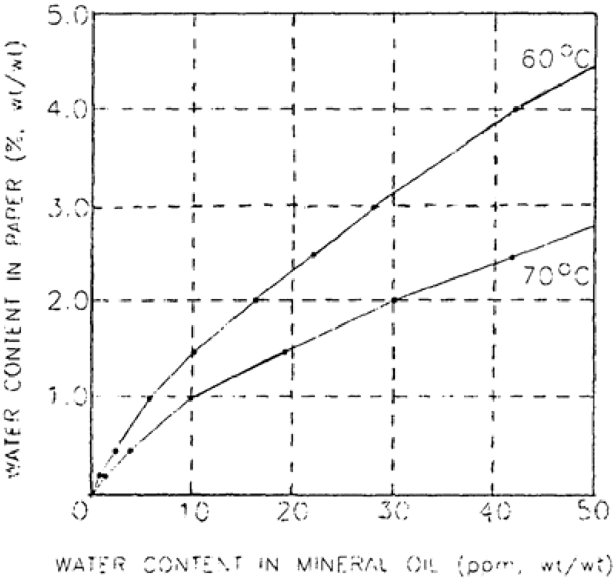

MOISTURE EQUILIBRIUM CURVES FOR 60 AND 70°C

FIGURE1