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POWER TRANSFORMER REFURBISHMENT: THE BENEFITS OF HYBRID INSULATION

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1. Introduction

In recent years, many changes have taken place in the utility industry concerning asset utilization, loading, maintenance and equipment application in general. Load profiles have increased while manufacturers, under constant and increasing cost pressures have fine-tuned their design techniques [1]. As with most electrical equipment, today's modern transformer is highly refined and technically mature. Although technology in the form of modern computers and sophisticated software has improved transformer reliability while reducing overall cost, the resultant transformers are also very lean by older standards, with minimal, if any reserve above the actual nameplate rated capacity.

Furthermore, optimisation of modern electrical power systems with higher utilisation of existing assets has frequently resulted in reduced maintenance programs by utilities, especially for large power transformers. Overall system reliability and transformer life have subsequently declined in many cases as a consequence of these changes. The industry-wide concern over these strategic changes is evidenced by the recent extraordinary interest in transformer monitoring equipment and techniques for condition assessment and field re-processing. A great deal of energy is expended in an effort to understand the current condition of an installed transformer by assessing the remaining life or determining the life lost during an emergency event. This attention is mostly oriented toward improving reliability under these new, more severe operating conditions.

To complicate the situation, the availability of funds for capital investment has also declined on an international scale, for various regional reasons. All of these factors have combined to favour the application of less conventional techniques in power transformer refurbishment, such as taking advantage of hybrid insulation technology. This "Hybrid" concept allows much greater flexibility when repairing failed transformers. It can also be seen by utilities as advantageous when anticipating failure of old conventional mineral oil filled units, especially when emergency conditions may be common on such units. It also brings the advantage of giving more value to the repaired unit by increasing its capacity and reliability, often on a lower $/MVA basis than a new unit.

Traditionally, power transformers use a combined insulation system, based on cellulose solid insulation immersed in insulating mineral oil, which limits the maximum continuous operating temperatures to 98°C for the cellulose and 115°C for the oil. However, by replacing this insulation system with a hybrid insulation system, composed of cellulose and high-temperature insulating materials, the unit load capacity may be substantially increased, while reducing the long-term ageing of the insulation. This technique of enhancing the thermal limits of the equipment, essentially eliminates the thermal restrictions associated with cellulose insulation, provides an economical

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solution for optimising the use of power transformers, increases operating reliability and may reduce fluid and equipment maintenance.

Development of hybrid insulation technology for liquid-immersed power transformers has evolved over a number of years and originated during the mid 1980’s as a solution for packing more power into a given space. The specialised high power density, high-temperature rise mobile transformers and mobile substations are still the best examples of this type of design. The current situation in the power industry together with global economic and environmental circumstances, have led to a renewed interest in this technology for repair and refurbishment.

2. Standardisation

Reflecting this interest and development of hybrid insulation technology, the Transformers Committee of the IEEE Power Engineering Society established a working group that subsequently produced a background paper in 1994 [2] and then a trial use guide in 1997. The document was reaffirmed and became a full guide in 1999 [3]. The purpose of this guide is to provide information on the application and use of high-temperature insulation in liquid-immersed power transformers and to provide guidance on the use of these transformers.

In 2001 a working group was established by IEC Technical Committee 14 to produce a similar standard. The document is titled: IEC 60076-14, Guide for the design and application of liquid-immersed power transformers using high-temperature insulation materials. One of the goals of the working group is to define some of the common techniques currently used in the design of both new and refurbished transformers. The term “Hybrid” has become a common term, but partial replacement of conventional insulation with high-temperature materials is addressed in the new document as well. Working Group 29 met for the first time in early 2002, producing the first CDV for circulation by the middle of 2003. The document was subsequently approved with only one negative ballot and should be published some time in 2004.

3. Hybrid Insulation System

Hybrid insulation systems are thermally optimised to exploit the capability of the high-temperature, high-cost materials by replacing the low-cost cellulose materials only where thermally warranted. These insulation materials are available as high-temperature enamels and paper for wire insulation and paper and board for other key insulation components. However, conventional lower temperature insulation materials continue to provide the bulk of the insulation requirements. High-temperature insulation typically includes the conductor insulation, static rings and axial and radial spacers that form the cooling ducts, as shown in Figure 1. The balance of the solid insulation is conventional cellulose material with mineral oil used for the liquid dielectric and cooling medium.

An interesting by-product of using high-temperature insulation is an improved winding space-factor. Since conventional solid insulation is typically operated very close to its maximum capability, cooling ducts are required to minimise hot-spot temperatures and to reduce the ratio of hot-spot to average winding temperature rise. In many cases, the average winding

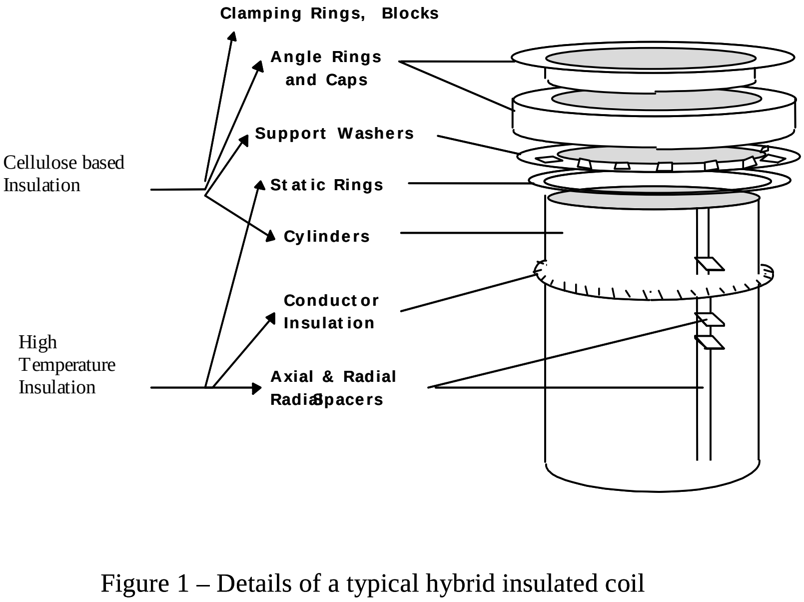

Figure 1 – Details of a typical hybrid insulated coil

temperature rise must be reduced in order to avoid exceeding the maximum hot-spot temperature rise even with many cooling ducts. Higher temperature insulation on the conductor allows an increase in hot-spot temperatures and the reduction of space allocated strictly for cooling of the winding. This is possible, even if the average winding temperature rise is not increased above conventional designs and in some cases, the cooling ducts may be eliminated entirely.

Using this technique, cooling ducts may then be redesigned and sized to provide mainly the dielectric requirements. The resulting space reduction reduces the coil size, allowing smaller overall dimensions and lighter weight. As an alternate, the increased available space may also be used for additional copper, thus allowing greater capacity with lower than expected losses, at the increased load.

4. Hybrid Insulation System Variations

More recently, additional insulation configurations have been introduced such as the semi-hybrid, where only the wires have high-temperature insulation and also mixed insulation systems, where only part of the windings (top and bottom for example), have high-temperature insulation.

The semi-hybrid technique can be used to advantage in applications subject to frequent short-term overloads, where the conductor insulation may see temperatures higher than 98^{o} C. The spacers remain below 98^{o} C, since they are cooled by the bulk oil flow that has not seen a significant temperature increase, due to the higher thermal time constant of the oil compared to the copper. Reduced gassing due to cellulose degradation is expected to improve oil quality, as the transformer passes through these short-term overloads. This design is typically a conventional 65 K average winding rise compared to hybrid units that are often designed to continuously operate at an average winding temperature rise as high as 95 K. Transformers operating in high ambient conditions such as in the Middle East or Africa can also benefit from this approach as well.

The advantages of the mixed insulation system are clear in the case of rectifier transformers that are subjected to high harmonic currents, which may cause overheating on both ends of the winding. The conventional strategy to protect the windings is to use additional cooling or additional copper, or a combination of both, thereby reducing the whole winding temperature, in order to reduce the winding hot-spot temperature. A mixed insulation strategy allows conventional average winding rises by protecting only the hottest areas, thereby reducing size and optimising material usage. This mixed insulation system strategy also helps to protect the windings from the effects of high cyclic loading, improving the thermal safety margin as well as the mechanical integrity that is at risk when cellulose spacers degrade due to heat.

5. Reduced Maintenance with High-Temperature Insulation

Under emergency conditions, loading beyond the nameplate capacity, although infrequent, is a necessity that may compromise reliability. It is well known and accepted that these overload conditions accelerate the aging of the insulation materials, which results in the generation of water and damaging gases, such as CO and CO$_2$. These contaminants eventually reduce the quality of the mineral oil until reprocessing of the oil is necessary or even replacement, under extreme conditions. Of course, the worst-case scenario is excessive aging that leads to premature failure.

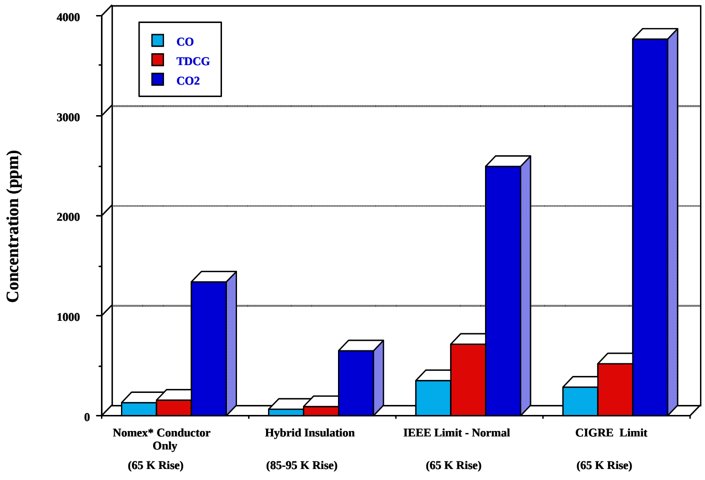

Figure 2 - Comparison of Dissolved Gas Analysis of Transformers

Developments in the United States during the late 1960's and early 1970's resulted in the use of high-temperature aramid fiber papers as wire insulation for improved mechanical performance in the winding structure of liquid-immersed transformers. Maintenance records of these transformers indicated that lower gas evolution was evidenced in these units due to the removal of cellulose papers from the hottest portions of the transformer winding. Even though these units were not thermally rated above the conventional 65 K average winding rise, the normal peak loading of these units should have resulted in normal thermal degradation of cellulose insulation. The records indicated the release of water, CO and CO_2 were lower than expected. The data of Figure 2 compare the standard levels considered by IEEE and CIGRE to be the first warning to users.

During the 1980's, the development of thick aramid board structures allowed the replacement of all the cellulose materials in the hot winding areas. This, in turn, allowed manufacturers and users to take advantage of these enhanced thermal properties and upgrade the thermal performance of the transformers to average winding rises of 95 K and even higher for some mobile transformer applications. The lack of gas evolution from the aramid polymer has shown much lower concentrations of dissolved gases in these units, even at high peak loads.

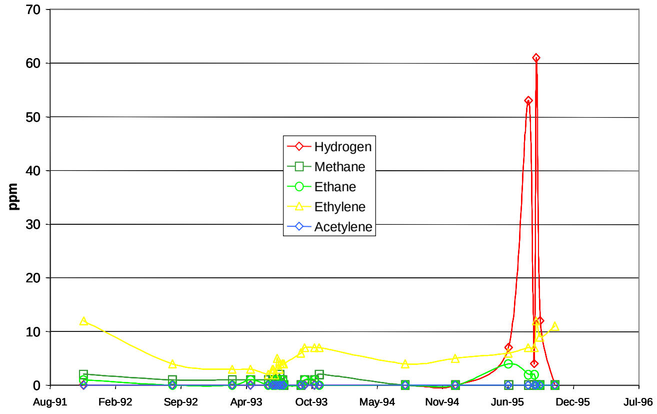

Fig. 3 : Gas in oil for a 30 MVA substation transformer – Oil originated

Generally the mineral oil is recognised to be the weak point when subjected to high-temperatures in areas close to conductors. The degradation of mineral oil when subjected to temperatures from 150^{o} C to 500^{o} C will produce large quantities of low molecular weight gases [4], such as hydrogen (H_2) and methane (CH_4), and also trace quantities of higher molecular weight gases, such as ethylene (C_2H_4) and ethane (C_2H_6). The graph in Figure 3 shows the evolution of gas generation over a 4-year period for a substation transformer after refurbishment. Note that the generation of Hydrogen reaches a maximum level of about 60 ppm, but then returns to negligible generation after the event. No generation of the other gasses is indicated, except for Ethylene, which remains around 10 ppm. This gas evolution graph indicates that no continuous thermal degradation of the oil occurred, even though the transformer was designed for a 95 K average winding rise.

The graph in Figure 4 plots the gases potentially resulting from cellulosic insulation degradation. Again, the evolution graph indicates that no thermal degradation by-products were extracted from the solid insulation.

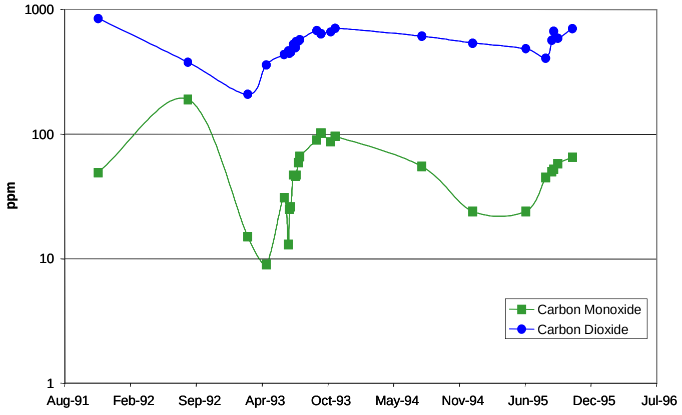

Fig. 4 : Gas in oil for a 30 MVA substation transformer – Solid originated

Substantial improvements in the mechanical stability of the insulation structure are a result of the greatly improved compression resistance of aramid spacer board. Studies have indicated that these materials have no loss in thickness at temperatures up to 150°C. This compares to a loss of 4% per year in the thickness of high-density cellulose spacer boards aged at 135°C. Even greater loss in thickness is experienced for cellulose at 150°C, which can be developed at peak overloads of 25% in conventional transformers. This loss of thickness and subsequent loosening of the windings can result in reduced short circuit resistance and weakened winding strength. Routine maintenance by tightening of the windings is necessary to correct this problem. With hybrid insulation systems using aramid fiberboard, this tightening may no longer be necessary, eliminating a maintenance step, while preserving the integrity of the windings. The data of Figure 5 were developed using 100 mm stacks of spacer board, which were dried and impregnated with mineral oil and initially compressed over the first 4 days. The test was terminated after 250 days with essentially no change in thickness of the aramid stack.

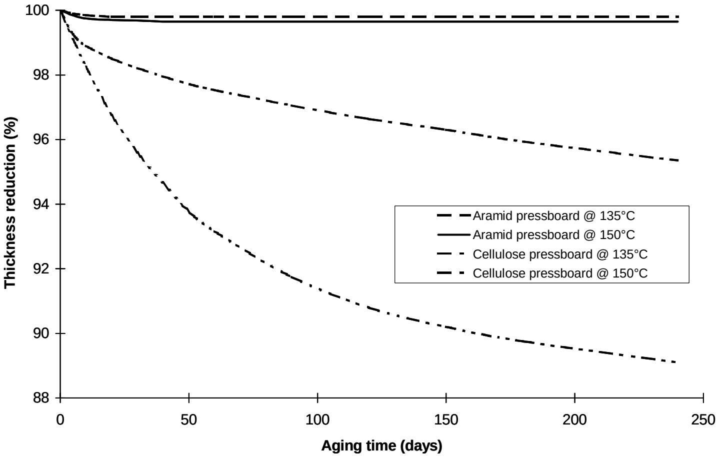

Fig. 5 : Static compression of cellulose board and aramid board under 10 MPa

Some repair applications require thicker aramid sheets for the occasional layer winding. To support this need recent testing has been conducted to provide additional test data on the electrical properties of aramid paper in mineral oil. Figure 6 shows the breakdown and impulse voltage strengths of various calendared aramid paper thickness. Although the materials were tested in sheet form, the thin grades (0,05 mm or 0,08 mm) are generally used as wire wrap and the thicker grades (0,13 mm and above) tend to be more suitable as layer or structure insulation.

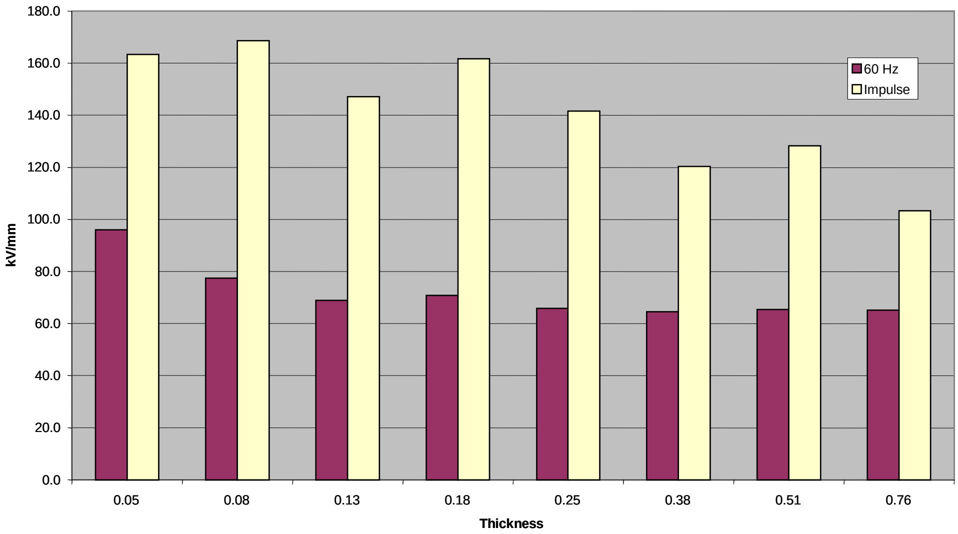

Fig. 6 : Dielectric strength of calendared aramid paper in mineral oil

6. Hybrid Technology Applications

A power transformer failure is always an event of multiple consequences. A classic example is an industrial line shutdown with a severe economic impact due to a blackout from a power loss on the grid. When determining the appropriate refurbishment strategy, analysis of the failure may indicate the need for additional load capacity or additional overload capability or simply enhanced reliability. A number of strategies are available to address the capacity issues using hybrid technology. In some cases, oversized units have even been “downsized” during a repair in order to reduce the base capacity, thereby reducing the cost of the repair, reducing losses and increasing the available overload capacity.

The following two examples illustrate the wide range and size of units that have taken advantage of some the many hybrid strategies and techniques.

6.1 Application to the excitation units for a nuclear power plant

A 5 MVA single-phase transformer was retrofitted using aramid paper, in order to improve reliability in case of overloading, to obtain better thermal performance and to extend lifetime. The transformer installation is shown in Photo 1.

For this retrofit, the following steps were taken: on the HV winding, the cellulosic material on the conductors was replaced by an aramid paper. In addition, the cooling of this unit was changed from an ONAN to an OFWF solution.

The solution used here represents a semi-hybrid insulation system according IEC 60076-14.

Photo 1: Unit in service

6.2 Large New Transformer for Improved Reliability

Recently a large utility in Brazil purchased a transformer specifically designed for reduced maintenance and improved reliability. Although not a refurbishment example, this unit illustrates the changing strategies of utilities today.

The 230 kV, 180/240/300 MVA unit shown in Photo 2, was constructed using hybrid insulation and conventional mineral oil. Of the sixteen configuration options, the three-phase hybrid design was selected as the most reliable option with the lowest total owning cost. The unit also provides a bonus of a 28% continuous overload capacity with no loss of insulation life.

Photo 2: Large Power Transformer

7. Conclusions

Many changes have taken place over the years in the hybrid technology. This technology that was developed jointly in the United States and Europe during the 1980's, has gained popular usage by emerging countries throughout the world, including recently in Brazil, Korea, China, Argentina, Paraguay, South Africa, Taiwan and Australia. The design techniques and applications have matured as standards were developed by IEEE and now more recently by IEC as well.

There are many opportunities today to take advantage of hybrid, semi-hybrid and mixed insulation technologies in transformer design, construction and performance. The use of aramid and other high-temperature materials can provide enhanced performance when used with traditional mineral oil by providing opportunities for lower size and weight, increased power or overload capability, improved reliability and reduced maintenance. Hybrid insulation technology is growing and expanding as it matures and is playing an increasingly larger role in the changing landscape of the modern power system.

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