Impact of Local Overheating on Conventional and Hybrid Insulations for Power Transformers

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ABSTRACT

For more than a century, conventional mineral oil/cellulose insulation is being used as main insulation for power transformers. The life span of these major assets is determined amongst others by the insulation system's mechanical resistance to withstand short circuit current forces. Since cellulose paper aging is accelerated by temperature, moisture and oxygen, poly-aramid-based synthetic insulation paper, with better thermal stability emerged for application in transformers. However the relatively limited number of studies on hybrid insulation and the cost of aramid paper still limit their use in distribution transformers. This contribution attempts to demonstrate that despite the high cost of aramid paper, hybrid insulation could be used in large power transformers which represent a significant financial investment. To do this, the quality of mineral oil aged with hybrid solid insulation and the thermal aging of the cellulose paper of this insulation are investigated. Comparison was made with traditional mineral oil impregnated cellulose paper to provide a benchmark for comparison. The samples underwent thermal accelerated aging procedure according to ASTM-D1934 standard and, furthermore, were submitted to local overheating. The condition of oil samples collected from each aging vessel was assessed using several diagnostic techniques, namely the relative amount of the Dissolved Decay Products (DDP), Turbidity, and Interfacial Tension (IFT). The Degree of Polymerisation (DP_v) and Dissolved gas Analysis (DGA) were used to monitor the thermal aging of the cellulose paper samples. The results indicate that oil aged with hybrid solid insulation yield fewer decay products at some aging stages, especially after the application of a local overheating. The results also indicate that the cellulose paper within solid hybrid insulation is slightly less degraded compared to that of conventional insulation.

Index Terms - **Mineral oil, cellulose paper, hybrid insulation, poly-aramid, local overheating, decay products, degree of polymerization, carbon oxides.**

1 INTRODUCTION

POWER transformers are considered as capital investments in a country's infrastructure. They represent the heart of any transmission and distribution of electrical energy. The insulation system of power transformers typically has consisted of mineral oil as liquid insulation and cellulose paper as solid insulation for nearly a century [1, 2]. Thus, it is commonly known as conventional insulation. The role of the insulation system is paramount since it is one of the basic conditions for the proper functioning of transformers. From the viewpoint of designers, it is usual to oversize the insulation system to improve the dielectric behaviour under service conditions. However, the application of voltage combined with stresses from various sources (thermal, mechanical, electrical, environmental, etc.) and their mutual interactions reveals a number of parasitic phenomena that cause gradual deterioration and aging of the insulation. Under service conditions, mineral oil degrades and generate soluble and insoluble decay products; these later attack the cellulose paper, in turn, increasing oil decay products [3]. Moisture, oxygen, metal catalysts, temperature, etc., accelerate aging of cellulose paper and mineral oil. These conditions may results in an electrical breakdown. With the growing energy demand worldwide, it is essential to improve the design of power transformers. In the last decades, poly-aramid based synthetic insulations have emerged [4]. Poly-aramid-based synthetic insulation, mainly used for applications in fluid impregnated transformers,

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provides high levels of electrical, chemical and mechanical integrity. Its good electrical and mechanical properties along with the lack of degradation products such as water or gas are some of its additional features. The term "aramid" is derived from a composite of "aromatic polyamides" and describes a form of synthetic solid insulation commonly used in high temperature applications [5]. Its long-term resistance to high temperatures allows the life of electrical equipment to be extended. This reduces premature failures and acts as a safeguard in unforeseen electrical stress situations. Aramid paper first appeared in the design of some transformers as hybrid insulation (aramid paper was applied in the hottest areas whereas colder areas were insulated with cellulose paper). Thus far, investigations on aramid-based papers have revealed its potential since its aging process is slightly influenced by temperature, moisture, and metal catalysts [6-8]. In the literature many results exist concerning the aged mineral oil decay products partnered with cellulose paper [9-19]. According to these results, mineral oil aged with metallic catalysts yield more decay products than that aged without metallic catalysts. However, in the configuration of mineral oil aged with metallic catalysts and solid insulation (cellulose paper), cellulose paper acts as a filter for oil by absorbing decay products on its large surface area. When aging proceeds further, these decay products attack the cellulose fibers and that contributes to increasing such decay in the oil. Concerning hybrid insulation aged with mineral oil only a relatively small number of works have been published [12, 20, 21].

This study was undertaken to investigate the quality of mineral oil aged with hybrid solid insulation and the thermal aging of the cellulose paper of this insulation. Comparison was made with traditional mineral oil/cellulose paper insulation. The aim of this contribution is to attempt to demonstrate that despite the high cost of aramid paper, the hybrid insulation could be used in large power transformers which represent a significant financial investment.

2 BACKGROUND ON INSULATION SYSTEM

2.1 HYBRID INSULATION SYSTEMS

Hybrid insulation systems combines the advantages of two types of paper, especially long-term resistance to heat for aramid and good mechanical properties for cellulose [6]. Some of the technical data of typical cellulose and aramid papers are given in Table 1.

Table 1. Technical characteristics of cellulose and aramid papers [8].

Properties	Units	Aramid	Cellulose
Density	g/cm^3	0,75	0,95-1
Thickness	µm	80	100
Tensile strength -Lengthwise -Crosswise	N/cm	 65 39	 130 53
Maximal temperature	°C	>180	115
Water content as delivered	%	3-4	6-7
Water saturation limit at 20°C	%	12	16

Aramid paper is more expensive than cellulose, and it is used selectively in high temperature demanding applications, for example in traction transformers. In a hybrid transformer design, the colder areas of the transformer are insulated with traditional cellulose-based Kraft papers, whereas aramid paper is applied in the hottest areas (e.g. wrapped conductors, axial and radial spacers) [5]. This strategy permits the same sort of advantages as for wholly aramid systems, but obviously not to quite the same extent, as cellulose is still present in the transformer. High Flash Point (HFP) fluids are commonly used with these systems as well. Figure 1 presents two views of a hybrid insulation transformer. This figure shows that aramid paper is wrapped around the windings and the cellulose paper elsewhere.

Figure 1. Hybrid insulation transformer without before tanking [22].

According to the IEEE guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Power Transformers [23], the maximum temperature limits (windings temperatures) of hybrid insulation are higher than those of conventional insulation. Some of these limits are summarized in Table 2.

Table 2. Maximum temperature limits for conventional and Hybrid insulations.

Insulation system temperatures	Conventional (°C)	Hybrid (°C)
Average winding rise over ambient temperature	65	95
Winding hottest-spot temperature	120	170
Top oil temperature,	105	105
Cellulose hottest-spot temperature	120	120

2.2 OIL DEGRADATION PROCESS AND QUALITY ASSESSMENT

The insulating oils in service undergo irreversible changes in their physicochemical properties related to a set of reactional processes, which are crucial for their life span. These processes involve the aging of these oils. The simultaneous action of oxygen and the electric field in the presence of metals (metal catalysts) leads to such aging. The oxidation phenomenon is the most destructive factor. In the presence of oxygen, oxidation involves four main steps (initiation, propagation, branching and termination) [20]. According to these reactions, the by-products that result are [15]: alcohols (ROH), aldehydes (ROHO), ketones (RCO--R), esters (R--COO--R'), organic acid (R-COOH), acid anhydride

((RC(O))2O), water (H_2O), carbon oxides, light hydrocarbons and peroxides (ROOH), which are intermediate products of the oxidation process. The action of these oxidation products leads to the formation of sludge deposits that can form on the surface conductive barrier, obstructing the oil flow passages and thus affect the heat transfer coefficient between the windings and the oil. The cooling system loses its efficiency and the resulting temperature rise accelerates oxidation and deterioration of the solid insulation. Monitoring and maintaining oil in pristine condition is essential to ensuring reliable operation of power transformers. Over the past years, several ASTM standards test methods have been developed to assess the condition of the oil degradation due to oxidation [24]. In these investigations the following three aging indicators were used:

2.2.1 DISSOLVED DECAY PRODUCTS or DDP (ASTM D6802)

This test method characterizes (by UV-VIS spectrophotometry) the relative level of dissolved decay products (peroxides, aldehydes, ketones, and organic acids) in mineral insulating oils of petroleum origin.

2.2.2 INTERFACIAL TENSION OR IFT (ASTM D 971)

This method provides a sensitive means of detecting small amounts of soluble polar contaminants and products of oxidation.

2.2.3 TURBIDITY (ASTM D 6181)

This test method uses a ratio-based turbidimetric optical system to measure the turbidity of insulating oils. Cloudiness or turbidity is attributed to matter with a diameter approximately 20 % of the wavelength of the incident light.

2.3 CELLULOSE PAPER DEGRADATION PROCESS AND AGING ASSESSMENT

The cellulose paper consists of approximately 80% cellulose, 12% hemicelluloses, 8% lignin and some mineral substances [25]. Chemical decomposition of cellulosic paper can be attributed to three different processes, namely oxidation, hydrolysis and pyrolysis. The pyrolysis reaction occurs at temperatures much higher than those to which the paper is subjected during the power transformer's operation. For this reason, the degradation of paper used in power transformer insulation systems is attributed to the oxidation and hydrolysis reactions alone. Moreover, the oxidation reactions are more significant because their activation energy value is lower than the activation energy of hydrolysis [26]. Under the combined action of oxygen and temperature, many degradation by-products are formed that can be used to assess the degradation condition of paper insulation. The most important ones are furans (2-furaldehyde, 5-methyl-2-furaldehyde, 2-acetylfuran, 2-hydroxymethylfuran), carbon oxides (CO, CO_2), water (H_2O), hydrogen (H_2), methane (CH_4) and low molecular weight carboxylic acids. The main cellulose degradation factor is acid hydrolysis, requiring water and acids. Other important factors are temperature and oil degradation products (Figure 2) [25].

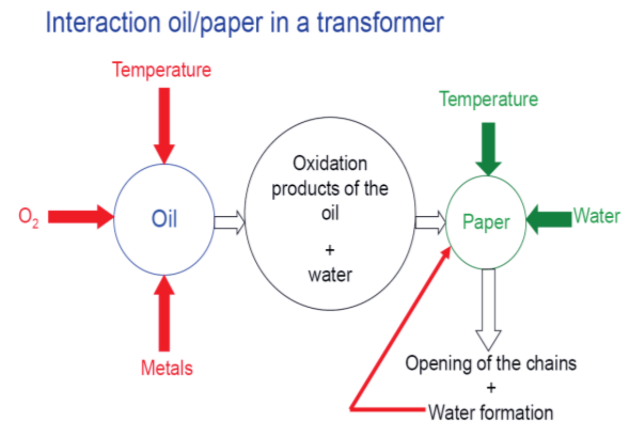

Figure 2. Link between oil oxidation and cellulose paper degradation [25].

Since the functional life of power transformers is determined by the life of its paper insulation, monitoring and maintaining the paper insulation in pristine condition is essential to ensuring reliable operation of these devices. The principal ASTM tests methods for the cellulose paper insulation assessment are: Degree of Polymerization (DP_v) according to ASTM D4243 [27], carbon oxides detection by Dissolved Gas Analysis (DGA) according to ASTM D3612 [24], Furanic Compounds (2-Furfuraldehyde «2FAL») according to ASTM D5837 [24] and Tensile strength (TS) according to ASTM D202 [28]. FDS (Frequency Domain Spectroscopy) techniques are also used [29]. Recently, some studies have revealed the potential use of Methanol (MeOH) as a chemical marker for paper insulation monitoring [25]. In these investigations the following two aging indicators were used:

2.3.1 DEGREE OF POLYMERIZATION (DP_V)

This is a direct diagnostic test method to assess the degree of aging of cellulose paper. This test method measures the specific viscosity of a solution of the paper in cupriethylene–diamine. From this measurement the intrinsic viscosity of the solution is deduced, and thereby the degree of polymerization is easily calculated.

2.3.2 DISSOLVED GAS ANALYSIS (DGA)

This is an indirect diagnostic test method to assess the degree of aging of cellulose paper. Among the eleven detected gases (Hydrogen-H_2, Oxygen-O_2, Nitrogen-N_2, Carbon monoxide-CO, Carbon dioxide-CO_2, Methane-CH_4, Ethane-C_2H_6, Ethylene-C_2H_4, Acetylene-C_2H_2, Propane-C_3H_8 and Propylene-C_3H_6), the carbon oxide (CO and CO_2) quantities are specifically used to evaluate the aging level of cellulose paper.

3 EXPERIMENTAL SETUP

Cellulose thermally upgraded Kraft paper (22HCC manufactured by Weidmann) and Aramid paper (Nomex T410 by DuPont) having a thickness of 80 µm, were dried under vacuum (<10^2 Pa (<1 mbar)) for 48 hours at 110 °C and then impregnated with dehumidified and degassed mineral oil (under vacuum for 24 hours). Accelerated thermal aging was conducted in laboratory conditions according to the ASTM-D1934 standard [24]. Two beakers containing 2000 ml of mineral oil (Nytro Lynx of Nynas) and metallic catalysts (each 3 g/l zinc, copper and iron of cuttings) were used. The first one included 180 g of cellulose paper, called conventional insulation, whereas the second beaker included 126 g (70% of 180 g) of cellulose paper and 54 g (30% of 180 g) of aramid paper, called hybrid insulation. Table 3 summarizes some of the main properties of the mineral oil study used in these investigations.

Table 3. Some of the physicochemical and electrical properties of the mineral oil under study.

Property	Unit	Test Method ASTM	Typical values
Total acid No.	mgKOH/g	D974	<0.01
Water content	ppm	D1533	<20
Breakdown voltage	kV	D877	>40
Colour		D1500	<0.5
Interfacial tension at 25°C	mN/m	D971	48

The mass ratio between the oil and the paper in each beaker was 10:1. Figure 3 presents the configuration of the two beakers. Both beakers were then placed in a convection oven at 115 °C for different periods of time up to 1000 hours. At the end of the thermal aging, paper samples were submitted to local overheating (hot spot) using a setup whose assembly diagram is shown in Figure 4 [30].

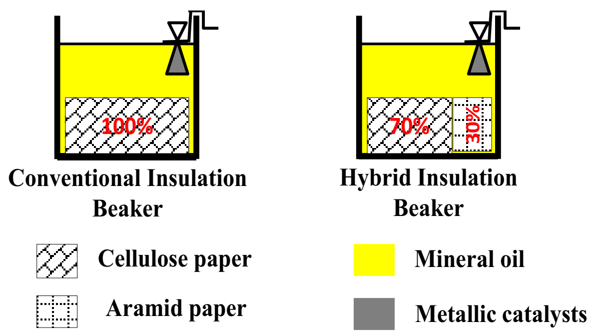

Figure 3. Beakers configuration for accelerated thermal aging.

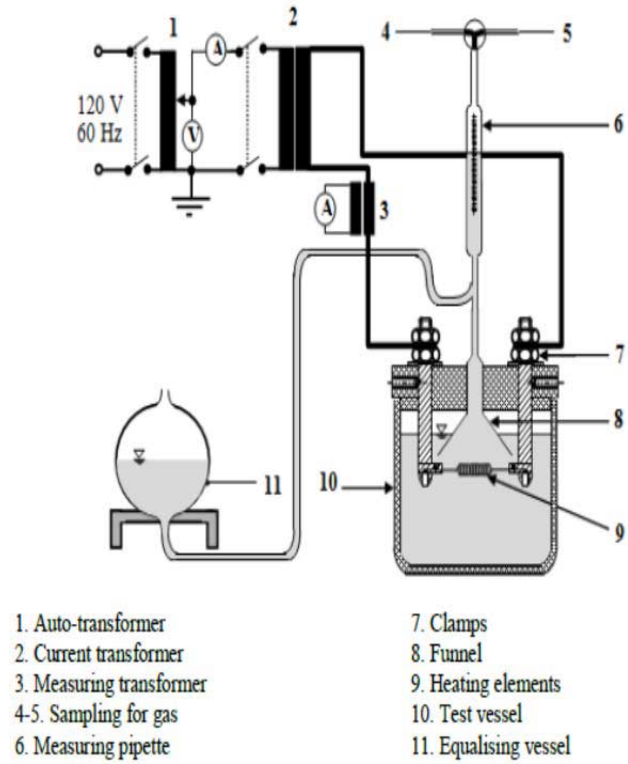

Figure 4. Schematic assembly of the equipment used for producing thermal stresses (local overheating) [30].

The experimental materials, the aging procedure along with the hot spot application procedure are summarized in Table 4.

During each test, a thermocouple (XCIB-K-1-1-3 by OMEGA) not illustrated in Figure 4 located very close to the heating wire was connected to a DM6802B digital thermometer to monitor the hot spot temperature. The average value of the hot spot temperature, calculated based on the measurements, was 280 °C.

Table 4. Summary of the experimental materials, the aging procedure along with the hot spot application procedure.

Materials	Impregnating/aging fluid (Nytro Lynx of Nynas)	Conventionnal Insulation (180 g of cellulose paper)	Hybrid Insulation (126 g (70% of 180 g) of cellulose paper and 54 g (30% of 180 g) of aramid)
Aging conditions	- 2000 ml of oil (Nytro Lynx of Nynas) and metallic catalysts (each 3 g/l zinc, copper and iron of cuttings) - Aged in convection oven at 115 °C for different periods of time (0, 500 and 1000 hours)		
Local overheating (hot spot) application on new and aged samples		**Step 1:** three layers of cellulose paper were wrapped directly on the heating wire (9) made of constantan (55% Cu-45% Ni).	**Step 1:** three layers aramid samples were wrapped directly on the heating wire (9) made of constantan (55% Cu-45% Ni)
		Step 2: 72 g of cylindrically wrapped paper samples were included in the test vessel (10).	**Step 2:** 72 g of cylindrically wrapped paper samples made of 50.4 g (70%) of cellulose and 19.6 g (30%) of aramid wrapped on the cellulose were included in the test vessel (10)
	Step 3: the vessel (10) was filled with 800 ml of aged oil.		
	Step 4: the equipment was energized and the power adjusted within the range of 200 ± 1 W.		
	Step 5: The oil and solid insulation samples were stressed for a total duration of 35 minutes.		
	Step 6: steps 4 and 5 were repeated five times for each sample under test.		
Measured parameters	Dissolved Decay products (DDP) Turbidity Interfacial Tension Dissolved Gases (CO, CO_2)	Degree of polymerization (DPv) of cellulose paper	

4 RESULTS AND DISCUSSIONS

4.1 STUDY OF THERMAL AGING OF THE CELLULOSE PAPER BEFORE AND AFTER LOCAL OVERHEATING

4.1.1 CARBON OXIDES ASSESSMENT

The key gas associated with cellulose paper overheating is carbon monoxide [31]. Thus its concentration in ppm within oils samples can be used as an indicator to compare aging level of cellulose paper in hybrid solid insulation with cellulose paper in conventional solid insulation. Cellulose paper overheating also produces high quantities of carbon dioxide [31]. The concentrations of carbon monoxide and carbon dioxide in ppm of the aged fluid samples were measured by DGA. The results obtained before application of local overheating are summarized in Figures 5 and 6 for CO and CO_2, respectively. However, the results corresponding to samples that underwent the local overheating are outlined in Figure 7 and 8, respectively. From Figure 5, it can be observed that the concentration of CO in the oil sample aged with hybrid solid insulation is slightly higher than the oil aged with cellulose paper. The same observation was noted for CO_2 (Figure 6). This result might either be traced to the action of pyrolysis phenomena, or to the action of oil decay products on the aging process of cellulose paper [25]. Aramid paper is known to be thermally stable [5, 6]; thus, it is almost immune to pyrolysis phenomena. Chemically, aramid is resistant to hydrolysis and oxidation such that oil decay products have no effect on it. Therefore it acts as an inactive solid partner [32] in the hybrid insulation system.

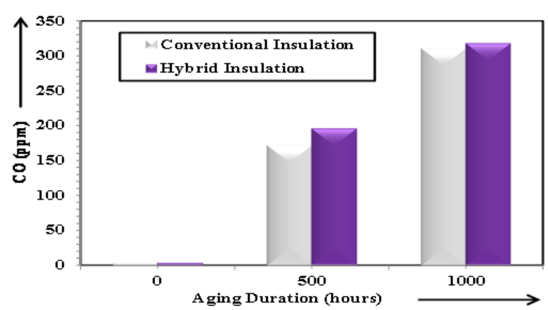

Figure 5. Concentrations of carbon monoxide in ppm as a function of aging duration.

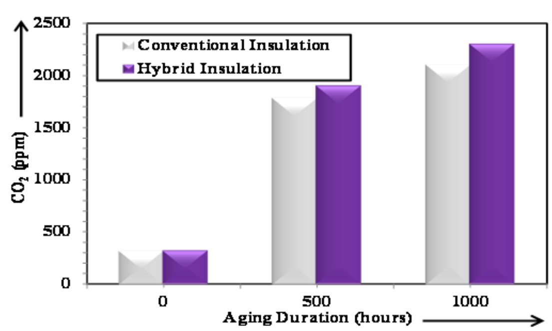

Figure 6. Concentrations of carbon dioxide in ppm as a function of aging duration.

From Figures 7 and 8, respectively, it can be observed that carbon monoxide and carbon dioxide concentrations of oil sample aged with cellulose paper are significantly higher than oil aged with hybrid solid insulation. It is well established in the literature [25] that cellulose paper under high temperature (local overheating) degrades, producing high concentrations of carbon oxides dissolved in insulating oil. Aramid paper's thermal stability [5, 6] means it is barely influenced by high temperature and does not produce carbon oxides dissolved in insulating oil.

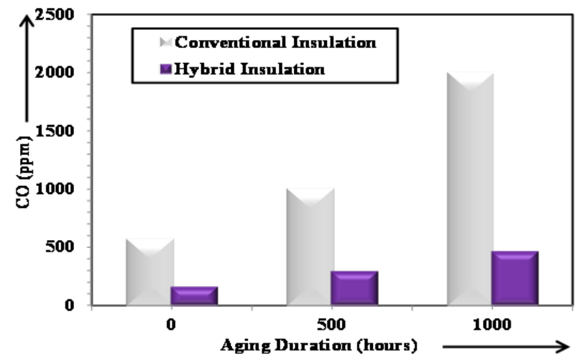

Figure 7. Concentrations of carbon monoxide in ppm as a function of aging after local overheating application.

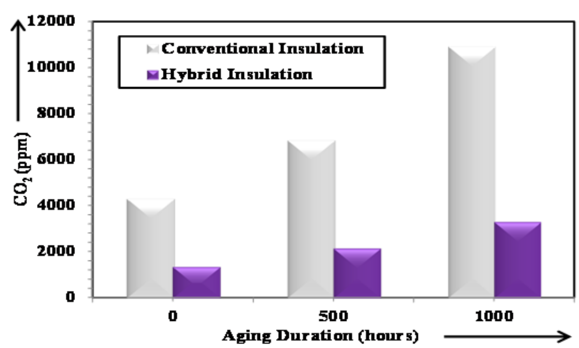

Figure 8. Concentrations of carbon dioxide in ppm as a function of aging after local overheating.

The IEEE Std 1276-1997 (Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Power Transformers) [23], presents DGA data collected on transformers that have a hybrid insulation (mobile and substation transformers). The concentrations of carbon oxides in these DGA data and those of laboratory accelerated thermal aging of hybrid insulation are presented in Table 5.

Table 5. Concentrations of carbon oxides from the IEEE Std 1276-1997 and from laboratory accelerated thetmal aging of hybrid insulation.

		Concentrations (ppm)	
		CO	CO_2
Transformer type	Mobile	555	2141
	Substation	91	1682
Hybrid insulation	500 hours of aging after local overheating	288	2100

According to Table 6, concentrations of carbon oxides in substation transformers are lower compared to those of mobile transformers. This difference is probably due to the

Table 6. Concentrations of carbon oxides in ppm and ratios of conventional insulation after local overheating application on the paper samples.

Aging Duration (hours)	Concentrations (ppm) CO	CO_2	Ratio
0	568	4250	7,48
500	1000	6800	6,8
1000	2000	10880	5,44

fact that mobile transformers are often used in case of emergency, so they are often overloaded. Moreover, its solid insulation (cellulose paper) is overheated, producing high concentrations of carbon oxides. Laboratory results for 500 hours of aging after the application of local overheating seem to approximate the levels of mobile transformers.

The ratio of CO_2/CO is sometimes used as an indicator of the thermal decomposition of cellulose. The ratio of CO_2/CO before and after application of local overheating for conventional and hybrid insulations are summarized in Figures 9 and 10, respectively.

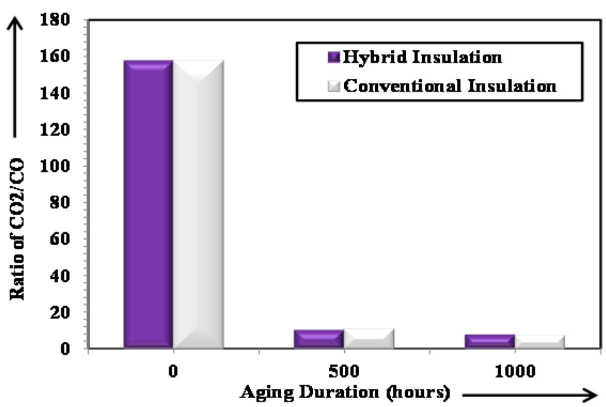

Figure 9. Ratio of CO_2/CO as a function of aging duration.

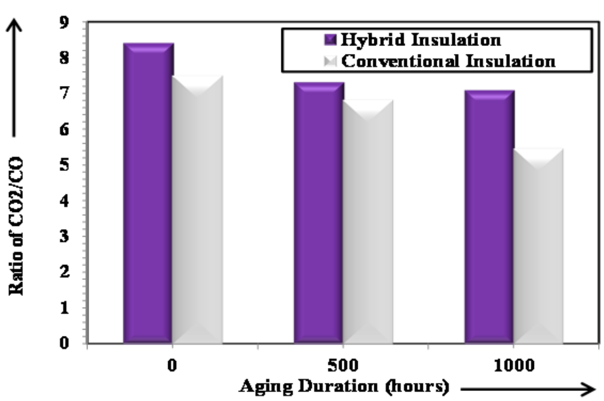

Figure 10. Ratio of CO_2/CO as a function of aging duration after local overheating.

From Figures 9 and 10 the ratio of CO_2/CO decreases during aging. In fact, during aging the concentration of CO increases; it is also inversely proportional to the ratio. According to IEEE standard C57.104-2008 [33] this ratio is normally more than seven. For the CO_2/CO ratio, the respective values of CO_2 and CO should exceed 5000 µL/L (ppm) and 500 µL/L (ppm) in order to improve the certainty factor, i.e., ratios are sensitive to minimum values. In the case of conventional insulation these conditions are satisfied after local overheating application. The concentrations of carbon oxides and ratios of conventional insulation after local overheating application on the paper samples are presented in Table 6. According to Table 7 the thermal decomposition of cellulose is clearly visible starting at 500 hours of aging (CO_2/CO<7).

4.1.2 DEGREE OF POLYMERIZATION ASSESSMENT

The degree of polymerization is an accurate way to measure the quality of cellulose and paper's mechanical strength [34]. When this factor decreases, it indicates the deterioration of the paper. Figure 11 depicts the results of the degree of polymerization measurements of cellulose paper for both types of insulation (conventional and hybrid) before application of local overheating, whereas Figure 12 displays the results after local overheating. Based on Figure 11, it can be observed that the DP_v of cellulose paper for both insulations decreases with aging duration. Furthermore, the DP_v of cellulose paper from hybrid insulation is slightly less compared to the DP_v of cellulose paper from conventional insulation. This test indicates that cellulose paper from hybrid insulation is slightly more degraded. These observations support results reported in Figures 5 and 6. From Figure 12, it can be noted that after the application of local overheating, the phenomenon is reversed. Indeed the DP_v of cellulose paper from hybrid insulation is higher compared to the DP_v of the conventional cellulose paper. These observations support the results reported in Figures 7 and 8.

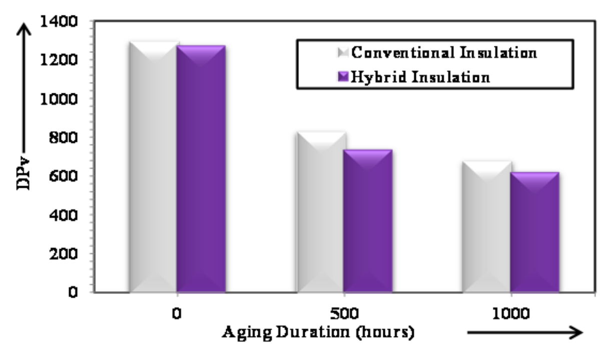

Figure 11. Degree of Polymerization of cellulose paper as a function of aging duration.

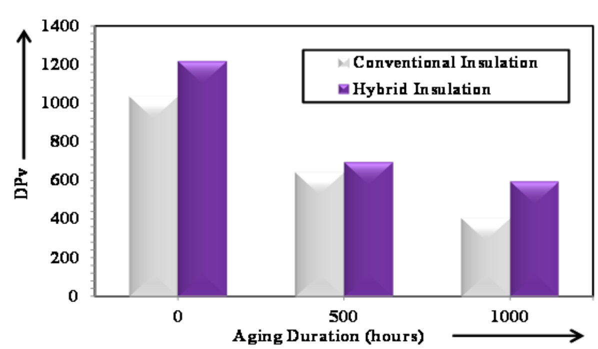

Figure 12. Degree of Polymerization of cellulose paper as a function of aging after local overheating.

Thereafter, rates of DP_v decrease of cellulose paper samples of conventional (RD_{Conv} %) and hybrid ($RD_{Hybrid}(\%)$) are estimated using respectively equation (1) and equation (2) below, and reported in Figure 13.

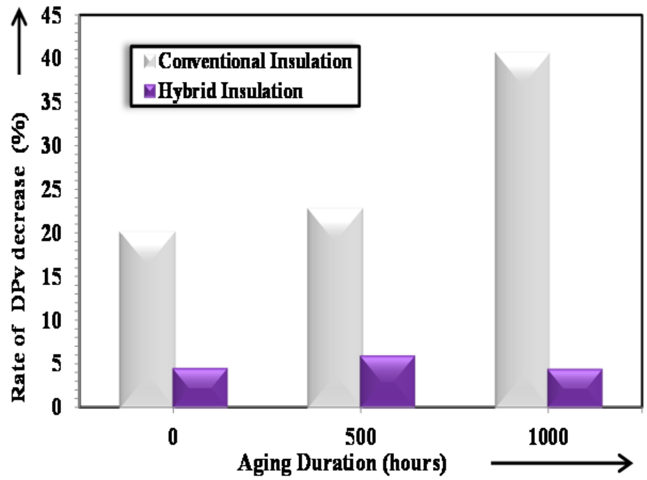

Figure 13. Rate of DP_v decrease of cellulose paper of conventional and hybrid insulation as a function of aging under local overheating effect.

$$RD_{Conv}(\%) = \frac{DP_{VAO}-DP_{VBO}}{DP_{VBO}} \times 100 \quad (1)$$

$$RD_{Hybrid}(\%) = \frac{DP_{VAO}-DP_{VBO}}{DP_{VBO}} \times 100 \quad (2)$$

Where DP_{VAO} and DP_{VBO} respectively denote the DP_v value after local overheating and before local overheating.

From Figure 13, it can be observed that the rate of DP_v decrease of conventional insulation is much higher than that of hybrid insulation, thus confirming that cellulose paper within conventional insulation is more degraded. It supports results reported in Figure 12. The rate of DP_v decrease ratio ($Ratio_D$) is estimated using equation (3) below, and reported in Figure 14.

$$Ratio_D = \frac{RD_{Conv}(\%)}{RD_{Hybrid}(\%)} \quad (3)$$

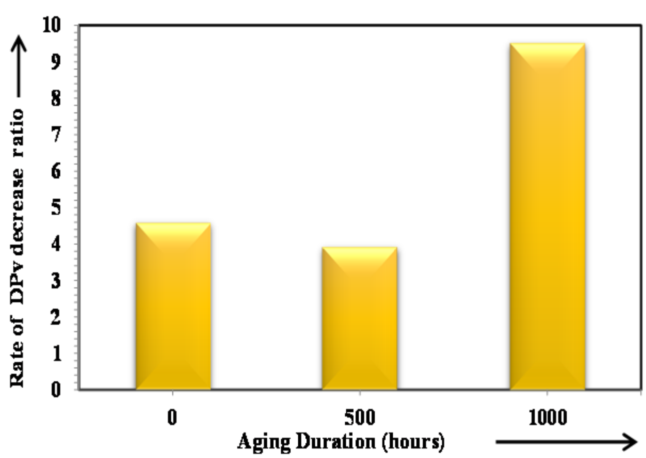

Figure 14. Rate of DP_v decrease ratio for cellulose paper within conventional and hybrid insulation as a function of aging under local overheating effect.

Figure 14 demonstrates that the rate of DP_v decrease ratio is higher than the value 9 at 1000 hours of aging. This outcome reinforces the results depicted in Figure 13.

4.2 OIL QUALITY BEFORE AND AFTER LOCAL OVERHEATING

4.2.1 DISSOLVED DECAY PRODUCTS ASSESSMENT

The relative amount of dissolved decay products (DDP) in the aged fluid samples was numerically characterized from the recorded absorbance curves according to ASTM D6802 [24]. The computed results of the DDP in the aged oil samples before application of local overheating was assessed and summarized in Figure 15, whereas the results corresponding to samples that underwent the local overheating are summarized in Figure 16. From Figure 15, it can be observed that the oil sample aged with cellulose paper contains less dissolved decay products up to ~750 hours aging compared to the oil aged with hybrid solid insulation. This disparity might be traced to the ability of cellulose paper to absorb decay products on its large surface area, thereby acting as a kind of oil filter [35]. When aging proceeds further the phenomenon is reversed, probably due to the fact that at a certain stage of aging, the cellulose paper becomes saturated in its capacity to absorb decay products. The decay products, when absorbed by the paper attack the cellulose fibres thus contributing to a further increase of DDP in oil [3].

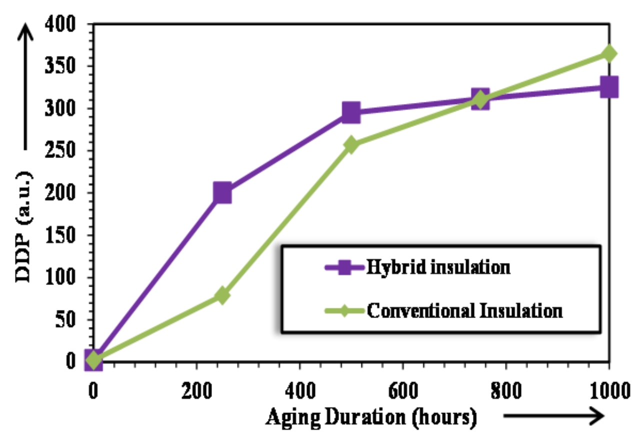

Figure 15. The relative content of the Dissolved Decay Products as a function of aging duration.

To elucidate this phenomenon, the absorbance curves before local overheating for 250 hours of aging (Figure 17) and 1000 hours (Figure 18) are plotted. From Figure 17, it can be observed that the absorbance curve of conventional insulation is below that of the hybrid insulation, whereas Figure 18 shows the opposite. The results reported in Figures 17 and 18 confirm those reported in Figure 15.

Chemically, Aramid is resistant to hydrolysis and oxidation and does not produce the levels of gas and water by-products as cellulose does. Its smoother surface and chemical structure are factors that help limit decay products within the aged oil. Unlike cellulose paper, its thermal stability allows for a reduction of its contribution to the

DDP increase in the oil [5, 6]; therefore, it acts as an inactive solid partner [32] in the hybrid insulation system. From Figure 16, it can be observed that the oil sample aged with hybrid solid insulation contains less dissolved decay products compared to the oil aged with cellulose paper. The phenomenon begins at around 750 hours aging before local overheating and endures as time continues.

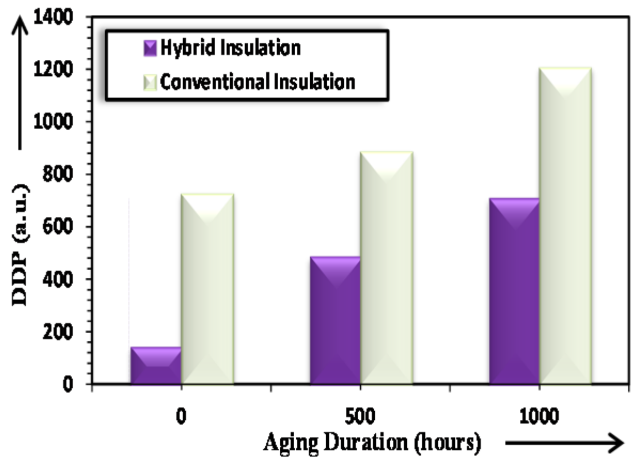

Figure 16. The relative content of the Dissolved Decay Products as a function of aging, after the local overheating.

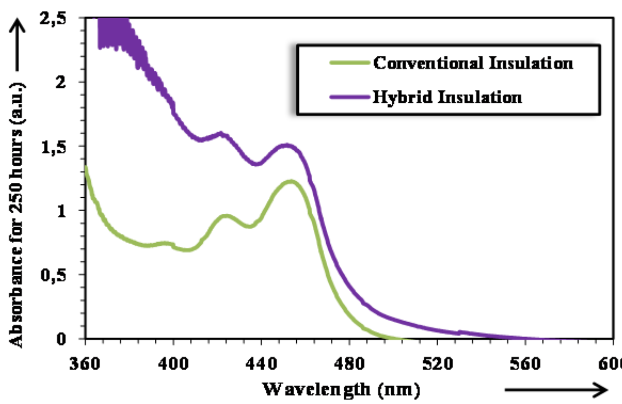

Figure 17. Absorbance curves for 250 hours of aging duration for conventional and hybrid insulations before local overheating.

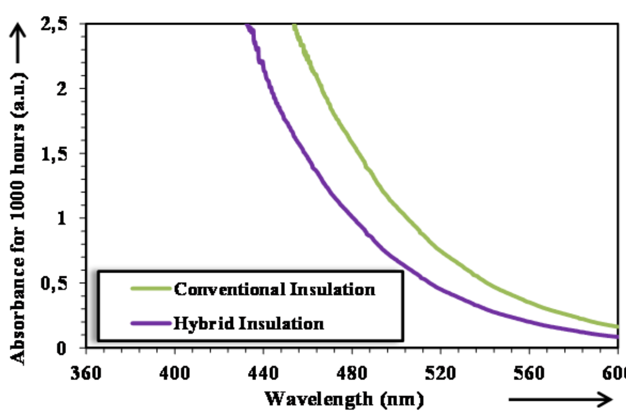

Figure 18. Absorbance curves for 1000 hours of aging for conventional and hybrid insulations before local overheating.

4.2.2 INSOLUBLE DECAY PRODUCTS ASSESSMENT

The relative amount of insoluble decay products (turbidity) in the aged oil samples before application of the local overheating was assessed and summarized in Figure 19, whereas data after the local overheating application are reported in Figure 20. Figure 19 displays that the turbidity of both oil samples increases as a function of aging duration in the same manner. From Figure 20, it can be noticed that after the application of local overheating, the turbidity in the oil aged with cellulose paper is significantly higher than that of the oil aged with the hybrid insulation.

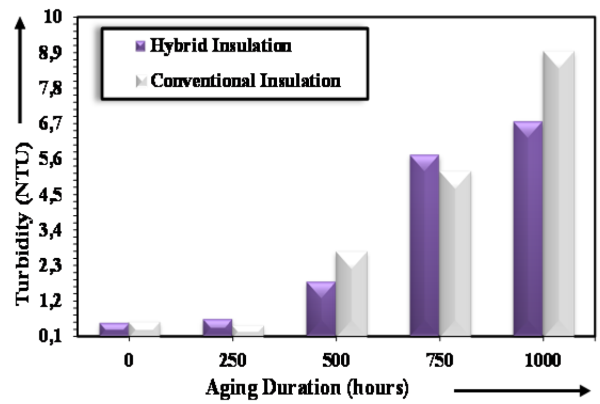

Figure 19. The relative content of insoluble decay products (Turbidity) in oil as a function of aging duration.

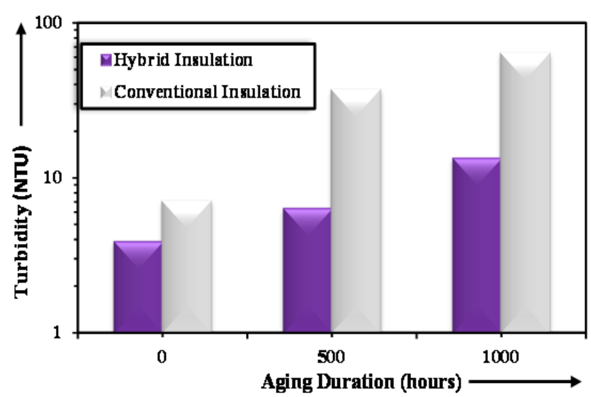

Figure 20. The relative content of insoluble decay products (Turbidity) in oil as a function of aging after local overheating.

It is well established in the literature [3] that cellulose paper degrades under high temperatures and produces insoluble decay products in oil. Such by-products do contribute to an increase in the oil's turbidity. Aramid paper is known to be thermally stable [5, 6]; therefore, it generates fewer insoluble decay products in oil.

4.2.3 INTERFACIAL TENSION ASSESSMENT

Figure 21 depicts the results of the interfacial tension (IFT) measurements for oil aged with cellulose paper and hybrid insulation before application of local overheating, whereas Figure 22 depicts the results after the local overheating. From Figure 21, it can be observed that the IFT of both oil samples decreases with aging duration. Furthermore, from Figure 22, it can be noticed that after the application of local overheating, the IFT of oil aged with conventional cellulose paper is significantly lower than that of the oil aged with hybrid insulation. These observations support results reported in Figures 19 and 20.

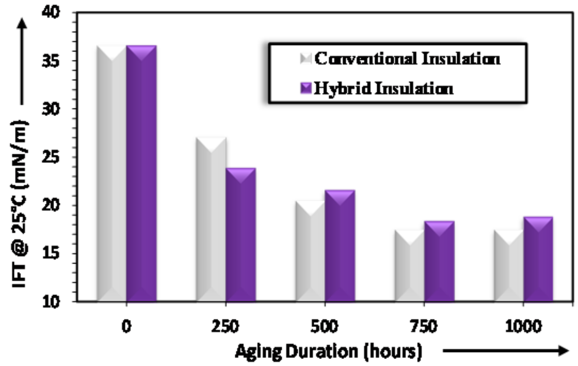

Figure 21. Interfacial tension (IFT) of oil as a function of aging duration.

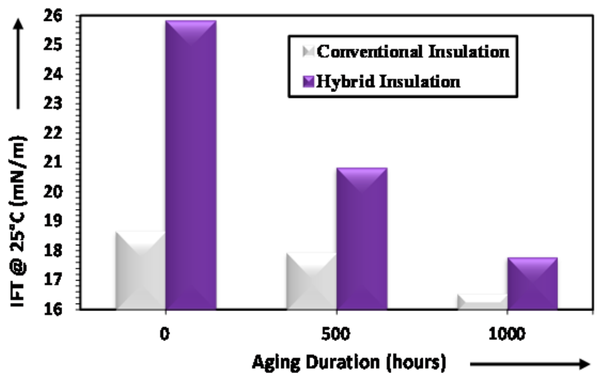

Figure 22. Interfacial tension (IFT) of oil as a function of aging after local overheating.

4.2.4 REPRESENTATION OF RESULTS IN PER UNIT VALUE

To better elucidate results obtained after application of local overheating concerning oil aged with hybrid insulation compared to that aged with conventional insulation. All the parameters associated to the three diagnostic techniques presented above were plotted in per unit scales (value measured after local overheating /value measured before local overheating) for unaged oil (Figure 23), 500 hours (Figure 24) and 1000 hours (Figure 25) of aging.

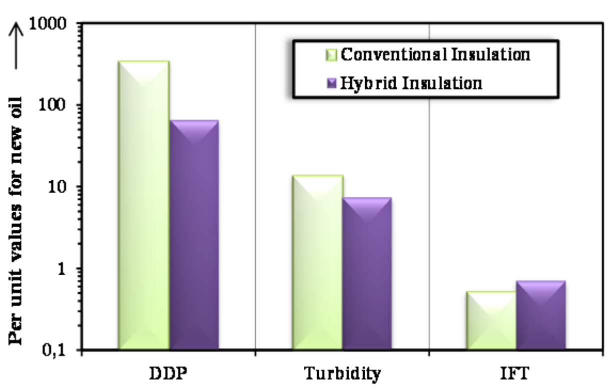

Figure 23. Comparative summary of the oil samples properties in per unit values (value measured after local overheating/value measured before local overheating) for unaged oil.

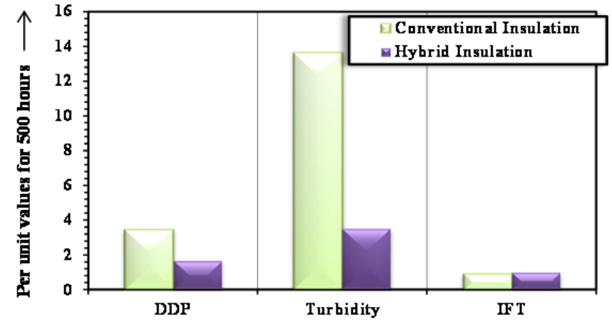

Figure 24. Comparative summary of the oil samples properties in per unit values (value measured after local overheating/value measured before local overheating) for 500 hours of aging.

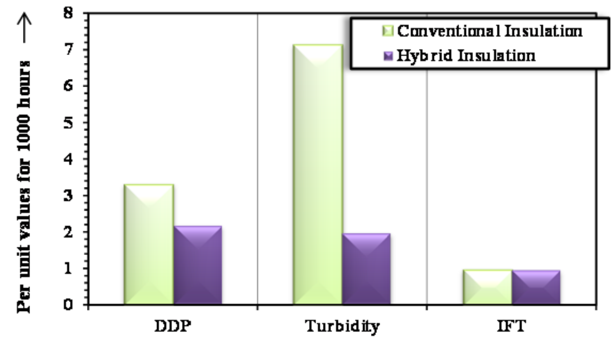

Figure 25. Comparative summary of the oil samples properties in per unit values (value measured after local overheating/value measured before local overheating) for 1000 hours of aging.

According to Figures 23, 24 and 25, the increase of DDP, and turbidity of the conventional insulation oil sample is higher than that using hybrid insulation–Oxidation products lower the interfacial tension and have an affinity for both water (hydrophilic) and oil [38]; at a certain level of aging, IFT stagnates. The IFT seems to be not too much affected by the type of paper. The aging of a blank oil (without paper) would have helped explaining that interfacial tension of the oil is almost the same as with the aged insulation and actually not dependent on it, but only on the temperature and oil aging.

5 CONCLUSIONS

Insulation (oil/paper) which degrades imperceptibly is desirable for the proper operation of power transformers. Unfortunately, under service conditions, the decades-old insulation system (mineral oil associated with cellulose paper), degrades under the impact of various stresses (thermal, chemical, electrical, etc.). In this contribution the condition of mineral oil aged with hybrid solid insulation (Poly-aramid-based synthetic insulation partnered with conventional cellulose-based paper) and the thermal aging of the cellulose paper of this insulation were studied. Comparison was made with traditional mineral oil cellulose paper to provide a base line for comparison. The condition of oil samples collected from each aging vessel was assessed using several diagnostic techniques, namely DDP, turbidity and IFT. DP_v and DGA were used to monitor the thermal aging of the cellulose paper samples. The compilation of the results during the normal aging reveals that there is not a lot of difference between paper and mixed insulation. However, aramid insulation has a significant advantage (as expected) in case of hot spot insulation. Oil aged with hybrid solid insulation yields fewer decay products at some aging stages, especially after the application of local overheating. The results also indicate that the cellulose paper within solid hybrid insulation is slightly less degraded compared to that in conventional insulation. These results suggest that the oil cellulose paper within a transformer using hybrid insulation would age/degrade less rapidly in comparison with the traditional insulation. Knowing that the decay products of oil contribute, in turn, to the degradation of solid insulation and also knowing the useful functional life of power transformers is determined by the life of the solid insulation, the use of hybrid insulation would probably enable higher long-term service reliability of transformers.

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