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EXPERIENCE WITH APPLICATION OF NATURAL-ESTER FILLED HV TRANSFORMERS IN MEXICO

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SUMMARY

Natural-esters are an attractive substitute for mineral-oils to fill liquid immersed power transformers. Its properties of biodegradability and high fire temperature point are used for special installations close to the general public or to natural sensitive geographic areas. Experience is now gained from various applications, nowadays natural-esters have been applied in high voltage power transformers as high as 400 kV, and more than 200 MVA, and initial concerns regarding of the properties of the fluids like oxidation stability and higher viscosity seem now been solved.

In this paper, the experience of a Mexican manufacturer is introduced, covering aspects of design and testing of more than 20 high voltage transformers filled with natural-esters. Mexican electrical industry, both private and public, has shown high interest in the application of high voltage transformers filled with natural-esters. Several dozens of applications now exist in the country with voltages as high as 230 kV, and the number of transformers is increasing.

The design of high voltage transformers filled with natural-esters has to be adapted to the different-than-mineral-oil properties. Different dielectric permittivity constant, as well as lower partial discharge inception and breakdown voltage levels for non-homogeneous electrical fields require modifications to the dielectric design and the insulation arrangement; the selection of the liquid-immersed ancillary equipment like tap changers, bushings, current transformers, etc. has to be according to the dielectric and thermal properties of the natural-ester liquid. The higher viscosity of the natural-ester mainly influences the need of different cooling solutions for the coils, as well as additional external cooling equipment. The calculation of average and local thermal gradients between windings and liquid has to be according to the heat transfer and fluids mechanics properties of the natural-ester liquid.

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The higher viscosity also has implications on impregnation and processing times before tests or energization. Details of some design rules are included in this paper as a rough guidance for retro-filling applications.

Special emphasis is given first to preliminary testing of the fluids, and next, to factory diagnostics of fluid and transformer's condition. Results of dielectric strength, power factor and moisture of the natural-ester liquid, prior to filling the transformer, are presented and compared to mineral-oil. Also, a comparative study for different characteristics of transformers filled with natural esters and mineral oil is presented, including power factor, capacitance, insulation resistance, temperature rise, dissolved gas Analysis, and others. Acceptance levels are presented as a proposal to the industry, as well as recommendations from the user point of view.

Handling of natural-ester liquids implies building new capacities and personnel skills for manufacturers and users. Diagnostics testing poses specific challenges, as natural-esters tend to produce different results from the most common diagnostic tests used in the industry (i.e. more intensive spontaneous gassing), and some accessories like on-line monitoring devices have to be adjusted accordingly.

KEYWORDS

Natural-ester liquids - HV transformers - comparison with mineral-oil - factory test results – diagnostics - temperature rise - dissolved gas analysis.

1. **INSULATION RESISTANCE (IR)**

The insulation resistance test is ample used in the industry for the evaluation of the insulation system drying and cleaning condition. A DC voltage is applied between windings and from windings to ground, the leakage current is measured at 1 and 10 minutes, and the IR calculated accordingly. Since a high value of resistance is expected, test results are usually reported in MΩ or GΩ. Although this test was originally developed for electrical rotating machinery, it has been applied to electrical transformers as well, and decades of experience have proved it may be useful to indicate whether the transformer insulation is in good condition before full rated or test voltage level is applied to the equipment.

The IR test results are subject to wide variation, and change with the voltage level applied, temperature of test, amount of solid and liquid in the insulation system (per design), and the type of solid and liquid materials used. No single or sufficient correction factors can be applied to account for all these sources of variation. Nonetheless, the test is used primary for comparison purposes among transformers constructed with the same materials, similar solid/liquid proportions, tested under the same voltage level and within a practical temperature interval.

The materials used in the insulation system are an important factor for the IR tests. Since this test is performed under DC, the resistivity of the materials affects the results. In the case of natural-ester, its volume resistivity is in the order of 30 x 10^{12} Ω-cm [1], while for mineral-oil is about eight times higher, or 250 x 10^{12} Ω-cm [2]. The figure 1 shows the IR test results for more than 20 power transformers (grouped in 11 designs) filled with soybean-based natural-ester, and compared with similar, same MVA and kV, transformers filled with naphthenic mineral-oil. The tests were according to IEEE standard C57.12.90 [3] section 10.11

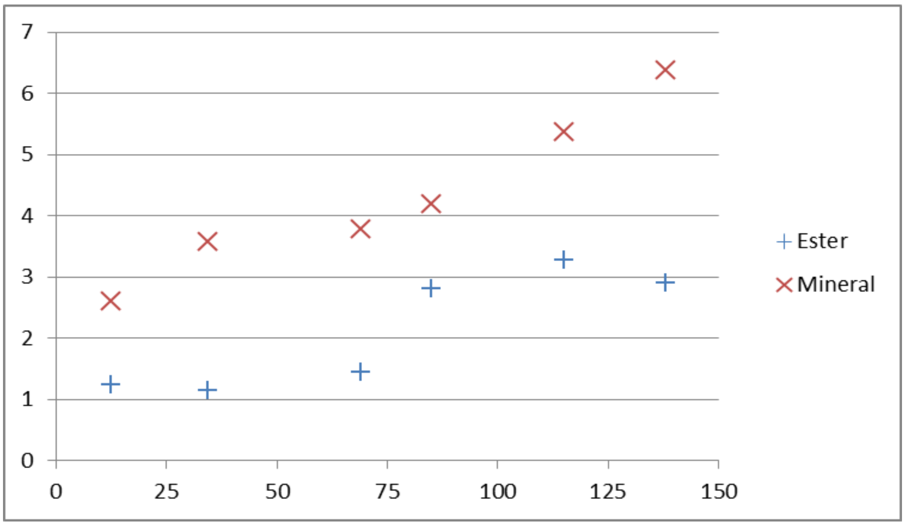

Figure 1: IR results in GΩ vs. kV of HV winding. For H/(X+G) at 1 minute and 2.5 kV DC

The IR of ester-filled transformers follows an increasing trend with transformer voltage, due to larger dielectric clearances, although weaker than their counterpart mineral-filled. As an average, the IR of ester-filled transformers is about half (50%) compared to the mineral-filled transformers. This response is similar to data shown in previous published papers [4].

2. **POWER FACTOR (PF)**

The insulation system PF (Cos φ) test is described by IEEE and ASTM [5] industry standards, and is extensively applied to transformers for the evaluation of the insulation system. IEC [6] standards also describe a similar test called DDF or Dielectric Dissipation Factor (Tan δ). Both tests are useful for detecting polar contaminants, and are applied to liquid samples, as well as to complete liquid-filled transformers.

AC sinusoidal voltage is applied between windings and from windings to ground, usually a voltage of 10-12 kV is used as coordinated with the transformer rated voltages. The voltage, current and their phase displacement are utilized to calculate the dielectric loss of the insulation, in order to evaluate its condition and readiness before rated or test voltage is applied. A low PF or DDF means lower dielectric losses.

The natural-ester liquid has inherently higher PF than mineral-oil, and this is related to the chemical composition of its molecules with oxygen atoms. This difference can be seen in figure 2, where a comparison between natural-ester and mineral-oil liquid samples is shown. The tests were according to ASTM standard D924 [5].

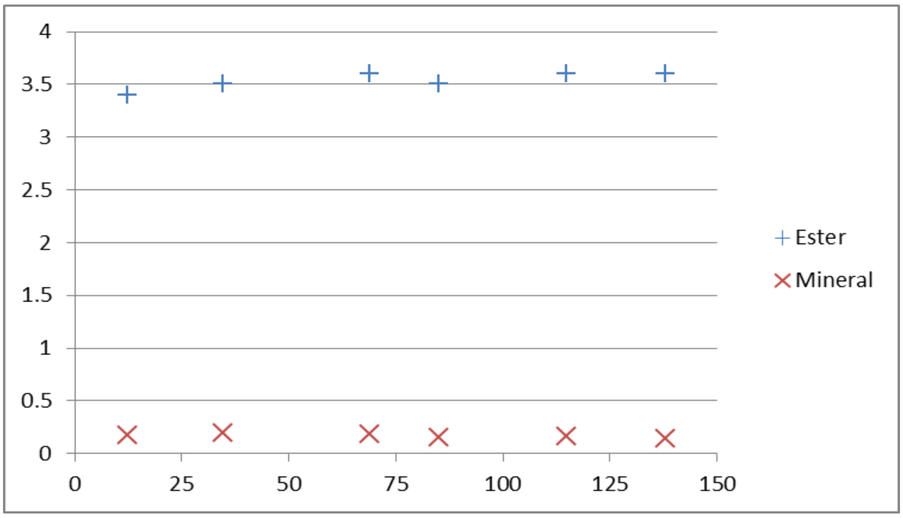

Figure 2: PF results in % vs. kV of HV winding. For testing liquid samples at 100 °C

As an average, the natural-ester liquid PF test results are 20 times higher than the mineral-oil, 3.5 % vs. 0.17 %. This big gap is not necessarily a problem, but just a different signature proper of the chemical formulation of the natural-ester liquid.

The effect of the liquid type is reduced when PF tests are performed on completely filled power transformers. The figure 3 shows the comparison of PF test results between ester-filled and mineral-filled transformers. The tests were according to IEEE standard C57.12.90 [3] section 10.10 at ambient temperature. As an average, the PF results of ester-filled transformers are 20% higher than the mineral-filled units. Both groups of data do not exceed the industry limit of 0.5%, typically used for power transformers filled with mineral-oil.

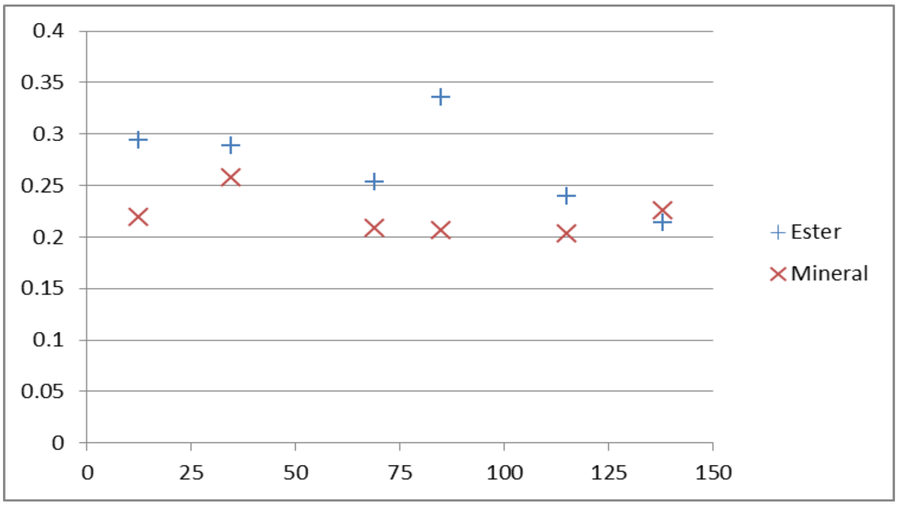

Figure 3: PF results in % vs. kV of HV winding. For H/(X+G) at 10 kV AC

3. CAPACITANCE (CAP)

The CAP of the insulation system is a by-product of the PF test. It is not commonly used for the evaluation of the insulation system condition, since it is less sensitive to contaminants than the PF itself. The CAP between windings and from windings to ground is a function of the geometry of the windings; the distance and the type of insulation material between them; and the temperature of test. Usually, the CAP is expressed in pico-Farads (pF).

The material property that primarily affects the CAP is the Relative Permittivity or Dielectric Constant (ε). It is the ratio of the capacitance with the insulation material under consideration to the capacitance under vacuum, for the same electrode geometry and distance. The dielectric constant for mineral-oil is 2.2, while for natural-ester is about 3.2 [1]. Figure 4 shows the comparison between ester-filled and mineral-filled transformers, being the ester-filled with higher capacitance results by about 30% in average. As expected, the CAP reduces with voltage level due to larger clearances involved.

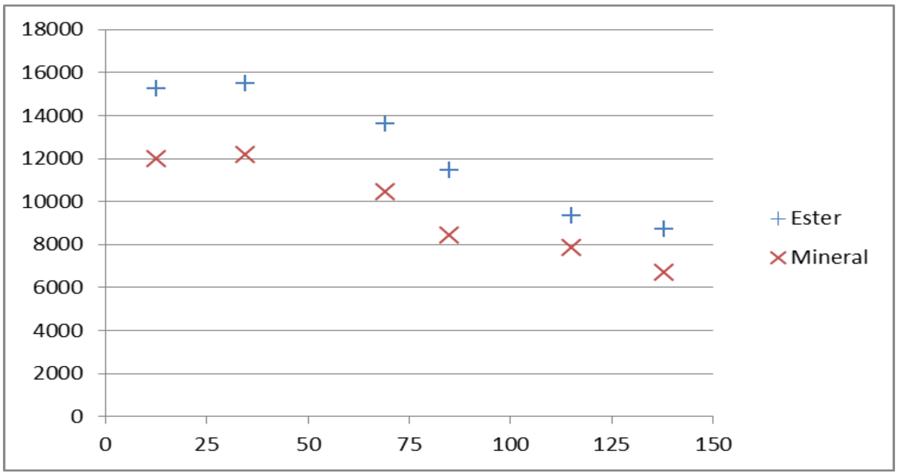

Figure 4: CAP results in pF vs. kV of HV winding. For CH+CHX at 10 kV AC

4. WATER CONTENT AND DIELECTRIC BREAKDOWN VOLTAGE (DBV)

Water is always present and dissolved in the insulating liquid. The amount of dissolved water in ppm or, more specifically, the Percent Relative Saturation (PRS) of water in liquid establishes its DBV. Therefore, it is desired to have low levels of PRS before final testing or field energization of power transformers.

The capability of dissolving water is different among the various insulating liquids available in the industry, i.e. natural-esters are much more hydrophilic than mineral-oils. The saturation level for natural-esters is about 1 000 ppm at room temperature [7], while the mineral-oil´s is just 55 ppm. Therefore, natural-ester would dissolve up to 18 times more water than mineral-oil, however both liquids behave dielectrically similar when compared in terms of PRS.

Figure 5 shows the results of dissolved water in samples of natural-ester and mineral-oil taken from power transformers before final tests. As an average, the natural-ester dissolves 15 times more water than mineral-oil. Both groups of data meet the internal limit level of 10% PRS at room temperature, i.e. 100 ppm for natural-ester and 5 ppm for mineral-oil. The tests were done according to ASTM standard D1533 [8].

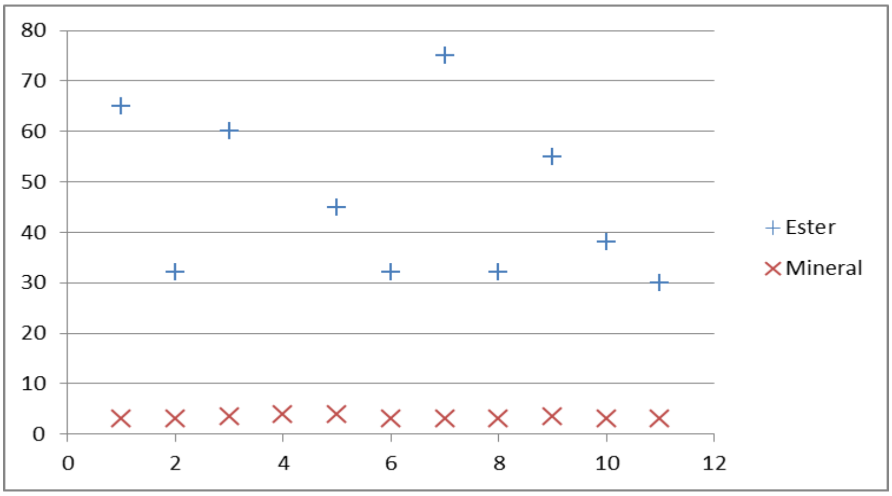

Figure 5: Water Dissolved in Liquid in ppm, using Karl-Fischer method at 25 °C.

The DBV of an insulating liquid is a measure of its ability to withstand electrical stresses under prescribed conditions. Figure 6 shows the DBV test results from samples of natural-ester and mineral-oil taken from power transformers before final testing. Both groups of data meet internal limit levels, as wells as the limit of 52 kV established by standards IEEE C57.106 [9] and C57.147 [10] for mineral-oil and natural-ester liquids correspondingly.

As an average, the DBV results of natural-ester samples were 13% below than the mineral-oil. This abnormal behavior could be related to the undetermined suitability of the test method ASTM D1816 [11] for liquids with viscosity higher than 19 mm^2/s at 40 °C, as is the case for the natural-ester.

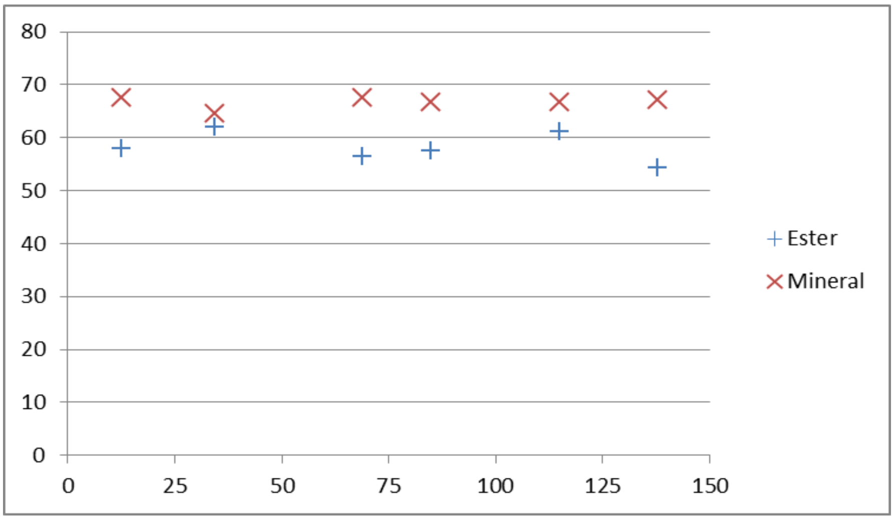

Figure 6: DBV in kV, vs. kV of HV winding per ASTM D1816 at 2 mm and 25°C

The transformers included in this database passed successfully all dielectric tests: lightning impulse, applied voltage and induced voltage. Those with measurement of partial discharges were with less than 100 pC, much less than the industry limit of 300 - 500 pC.

5. TEMPERATURE RISE TEST

The temperature rise test is an important design test used to verify the transformer will not operate at higher temperatures than the materials capability. The average-winding / top-liquid temperature rise limits are established by IEEE standards as 65/65 K, while the IEC standards limit them to 65/60 K correspondingly. For some special applications, like higher ambient temperatures, lower temperature rise limits may be required, i.e. 55/55 K. These limits apply to cellulose-based insulation immersed in mineral-oil.

It has been published that natural-ester liquid increases the cellulose-based paper life [12], due to its higher water solution capability than mineral-oil. Although this improvement has been demonstrated through accelerated aging tests of sealed cells and distribution transformers, the industry has yet to increase the limits for transformers filled with natural-ester liquids. Which remain at 65/65 K or 55/55 K for average winding / top liquid temperature rise.

The heat transfer of a power transformer is a complex mechanism that involves many factors including: geometry of windings, tank and cooling equipment; amount and distribution of losses; ambient temperature, altitude and solar radiation of operation site; thermal properties of solid and liquid construction materials, etc.

The viscosity of natural-ester liquid is the main difference on thermal properties with mineral-oil, as shown in figure 7. At test temperatures, the natural-ester viscosity is about three times higher than mineral-oil´s [13]. This result in higher temperature rises for transformers with mineral-oil design, but filled with natural-ester liquid.

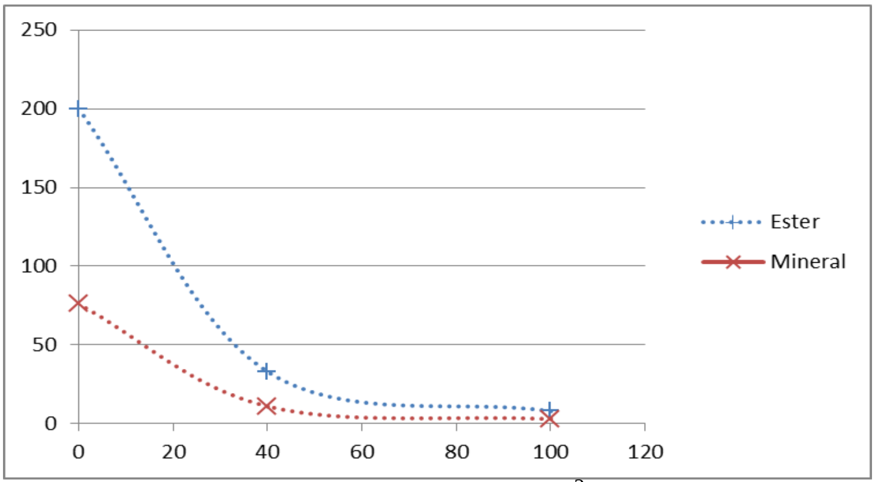

Figure 7: Liquid Kinematic Viscosity in mm^2/s vs. Temperature in °C

The temperature rise average results of more than 20 tests of transformers filled with natural-ester are shown in table 1. The majority have a temperature rise limit of 55 K for ONAN $_{base}$ and 65 K for ONAF $_{max}$. The last three rows show a comparison of test results vs. design values from mineral-oil heat transfer equations. The tests were done according to IEEE standard C57.12.90 section 11[3].

	ONAF $_{max}$	ONAN $_{base}$
TOR (K)	52.7	47.9
AOR (K)	35.1	33.7
TOR-AOR (K)	17.6	14.2
Grad. Wdg. (K)	13.1	8.5
Total Losses (kW)	238	117
MVA $_{ave}$	34.9	24.5
TOR vs. Calc (K)	6.5	1.9
AOR vs. Calc (K)	3.8	1.8
Grad. vs. Calc (K)	-2.2	-1.2

Table 1: Average Results of Temperature Rise Tests with Natural-Ester Liquid

The effect of the higher natural-ester viscosity can be seen in the difference TOR-AOR, which is about 4 K higher than the usual 10 - 14 K for mineral-oil [14]. The higher hydraulic resistance posed by natural-ester causes a reduced oil flow in the circuit and, therefore a larger temperature drop across the cooling radiators.

The TOR and AOR test results deviation from calculations increases with the capacity of the transformer, being the TOR at ONAF $_{max}$ the worst case. This means a different correlation between thermal gradients and losses, $\Delta T = k\,(q'')^x$, should be used in design equations.

The winding gradients do not follow the same pattern as the liquid temperature rises. On the contrary, the natural-ester gradient test results are lower than the mineral-oil calculations. This may be due to the larger-than-typical oil ducts utilized for better cooling in the windings.

6. DISSOLVED GAS ANALYSIS (DGA)

The DGA is ample used in the industry for evaluation of liquid immersed equipment. Decades of factory and field experience with mineral-oil filled transformers have produced guidelines for the identification and location of a probable problem. In principle, the nature of gasses associated with a problem in natural-ester are similar than those from mineral-oil, however the volume of gas produced varies with the type of liquid. [15]

The table 2 shows the DGA average results produced during the temperature rise tests of more than 20 natural-ester filled transformers, and compared to typical mineral-oil results.

Gas		Natural-ester, ppm	Mineral-Oil, ppm
H_2	Hydrogen	11.5	1.5
CH_4	Methane	1.2	0.5
CO	Carbon Monoxide	15	13
CO_2	Carbon Dioxide	55	48
C_2H_4	Ethylene	0.3	N.D.
C_2H_6	Ethane	45	N.D
C_2H_2	Acetylene	N.D.	N.D.
Hours of Test		30	24

Table 2: DGA results for Natural-Ester vs. Mineral-Oil, ASTM standard D3612 [16].

The carbon oxides are essentially the same for natural-ester and mineral-oil. Acetylene is non-detectable (N.D.) for both liquids, because this gas requires a big amount of energy to be produced, i.e. related to an electrical arc. Ethylene and methane are slightly higher (traces) in natural-ester. The main difference between liquids resides in the generated volume of hydrogen and ethane. These gasses are recognized in the literature as stray gassing for natural-ester liquids, while for mineral-oil these may be related to a probable problem. [17]

The different DGA Behavior of the natural-ester should be considered when attempting to evaluate a transformer filled with this type of liquid. There are standardisation efforts for evaluating DGAs from transformers in the field, but none to factory tests.

CONCLUSIONS

1.- The use of natural-ester liquids in power transformers has increased in the last years, mainly for transformers connected to the grid distribution system. This has opened a new field of knowledge for manufacturers and users. This paper presented the results of more than 20 power transformers manufactured and tested by a Mexican manufacturer in the last 3 years.

2.- The preliminary electrical tests of natural-ester filled transformers showed a different signature when compared to mineral-oil. This difference did not affect the performance during full dielectric tests for the transformers presented in this paper, but should be taken into account when utilized as diagnostics tools.

3.- The higher viscosity of natural-ester results in higher liquid temperature-rises in comparison with mineral-oil, and this difference increases with transformer capacity (MVA) and losses (kW). The heat transfer equations used for the thermal calculations should be adjusted accordingly for new, as well as retro-filled, transformers.

4.- The gas production, during factory temperature-rise test, of transformers filled with natural-ester is higher than their counterpart filled with mineral-oil. If this difference is not acknowledged, it could lead to wrong conclusions or diagnostics due to the high volume of stray gassing (ethane and hydrogen) produced by the natural-ester liquid.

BIBLIOGRAPHY

[1] Cooper Power systems, Dielectric Fluids Products, 1900 East North Street, Waukesha, WI 53188-3899, USA, Product Information Bulletin 00092, May, 2001

[2] Resistivity of Transformer oil at low and medium field strength. Harrison, N.L. Proceeding of the IEE, Volume 115, issue 5, 1968, pages 736-741

[3] IEEE C57.12.90-2010. IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulation Transformers

[4] Some Consideration for New and Retrofill Applications of Natural Ester Dielectric Fluids in Medium and Large Power Transformers Revisited. Moore, S.P. IEEE Power & Energy Society General Meeting, 2009, PES 09, pages 1-7

[5] ASTM D924-08. Standard test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids

[6] IEC 60247 Ed 3.0. Insulating Liquids – Measurement of Relative Permittivity, Dielectric Dissipation Factor (Tan d) and d.c. resistivity

[7] A methodology for Determining Water Saturation Limits and Moisture Equilibrium Diagrams of Alternative Insulation Systems. Jovalekic, M, et al. 2011 IEEE International Conference on Dielectric Liquids (ICDL), 2011, pages 1-5

[8] ASTM D-1533-12. Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration

[9] IEEE C57.106-2006. IEEE Guide for the Acceptance and Maintenance of Insulating Oil in Equipment

[10] IEEE C57.147-2008. IEEE Guide for the Acceptance and Maintenance of Natural Esters Fluids in Transformers

[11] ASTM D1816-12. Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids using VDE Electrodes.

[12] Aging of Kraft Paper in Natural Ester Dielectric Fluid. McShane, C.P., et al. Proceedings of the 2002 14th IEEE International Conference on Dielectric Liquids. ICDL 2002 Pages 173-177

[13] Cooper Power systems, Dielectric Fluids Products, 1900 East North Street, Waukesha, WI 53188-3899, USA, Product Information Bulletin 99048, August 2001

[14] Design and Test Experience with Natural Ester Fluid for Power Transformers – Update. Smith; S.D. Beaster, B.L. IEEE Power & Energy Society Meeting, 2009, pages 1-3

[15] The Duval Triangle for Load Tap Changers, non-Mineral Oils and Low temperature Faults in Transformers. Duval, M. IEEE Electrical Insulation Magazine, Vol. 24, issue 6, 2008

[16] ASTM D3612-2009. Standard Test Method for Analysis of Gases Dissolved in Electrical insulating Oil by Gas Chromatography.

[17] Gassing Behavior of Alternative Insulating Liquids Under Thermal and Electrical Stress. Jovalekic M. et al, Conference Record of the 2012 IEE International Symposium on Electrical Insulation. Pages 490-493