Natural Ester Fluid: The Transformer Design Perspective

T. B. Marchesan and A. J. Fanchin

***Abstract*--This paper presents the perspective of employ natural ester fluid to high voltage and high power transformers. Some studies that have been done in the literature about the dielectric characteristics of natural ester fluid point to some differences, mainly in streamer propagation and long gap distance tests, when compared to mineral oil. However, all of the tests previous done, in this issue, were based on laboratory controlled conditions. This study presents the experimental results for two prototype power transformers in the voltage class of 69 kV and 245 kV, manufactured and electrically stressed to their limits in natural ester fluid. The results address to some differences in the dielectric characteristics of natural ester fluid, mainly in the presence of non-uniform electric field and long gap distances.**

***Index Terms*- Design perspective, High-Voltage, Impulse test, Power transformers, Natural ester fluid.**

I. INTRODUCTION

NATURAL ester liquids are increasing their participation on the market as the insulation fluid for high-power transformers. The ready biodegradability characteristic, high fire point (> 300 ^{o}C) and the possibility to increase the paper insulation life are the most important points that may be addressed [1]-[5].

Although mineral oil is still being the most popular insulation and cooling liquid employed in the transformer industry, the research evolution in the dielectric capability field of natural ester fluids are making possible the design of transformers up to 245 kV, as shown in Fig. 1.

The mainly disadvantages of the natural ester fluid are considered to be the higher viscosity and lower oxidation stability when compared to mineral oil. The former makes influence on the transformer cooling system and the second limits its use to sealed units [6].

For the cooling system, some design changes have to be done in order to maintain the hot spot temperature rise below the standard limits as presented in [7].

The lower oxidation stability shall be considered on the design of sealed units and during the manufacture process of the equipment, manly when already impregnated parts are exposure to the ambient. It could be observed that the polymerization of the fluid on the surface of the solid insulation of the transformer reduces the dielectric behavior for creep discharge in about 10-30 % (this percentage is under study). Based on this, it is essential to control the exposure to air of all impregnated parts of the transformer in case of a repair for more than 2 or 3 weeks, depending on the factory environment conditions.

The lighting impulse breakdown test is one of the most important tests used to certify the dielectric capability of insulation fluids for power transformers. A lot of papers have been published in the literature about this topic and some of them point to no difference between mineral oil and natural ester fluid dielectric characteristics [8]-[10].

However, some laboratory studies have shown differences in the dielectric characteristics of both fluids for large gap distances and streamer propagation [11]-[15].

This paper presents the design perspective of power transformers employing natural ester fluid as the insulation and cooling medium. The study has been done based on the impulse test in two prototype transformers. This study considers the real transformer manufacture and test conditions.

The results presented are part of a large study that has being done in this field with two prototype equipments in 69 kV and 230 kV considering a basic impulse level (BIL) up to 1300 kV.

The single-phase 230 kV prototype, designed to the dielectric tests in natural ester fluid, is presented in fig. 2.

Fig. 1. A 245 kV / 100 MVA three-phase transformer in natural ester fluid manufactured by WEG T&D to PETROBRAS (brazilian oil company).

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Fig. 2. The single-phase 230 kV tested prototype up to impulse level of 1300 kV

II. Finite Elements Analysis

The electric field analysis was done on the critical point where the discharge occurs during the dielectric tests that have been done on the factory for the 69 kV high-power transformer prototype (fig. 3).

The distribution of the voltage stress between the various insulation materials during the impulse test depends on the permittivity (dielectric constant) of each material.

Natural ester fluids have higher permittivity (3.3) compared to mineral oil (2.4) at 25 ^{o}C. The higher value of the dielectric constant for natural ester fluid is closer to the cellulose dielectric constant (~4.6) improving the electric field distribution along the transformer insulation materials [16].

Simulations of the electric field distribution in natural ester and mineral oil are shown in fig. 3, considering the differences of insulation materials dielectric constant in both designs.

It is presented in fig. 3a and 3b the nonuniform field on the top of the winding with no static ring.

In fig 3c and 3d the difference on the voltage stress in the interface between paper and oil is highlighted.

It could be observed that in the design employing natural ester fluid there is an increase in the voltage stress in the paper conductor insulation, decreasing the stress voltage in the oil, i.e., If the same design is considered, the stress in the oil is reduced by the use of natural ester fluid due to the relation between materials dielectric constant values.

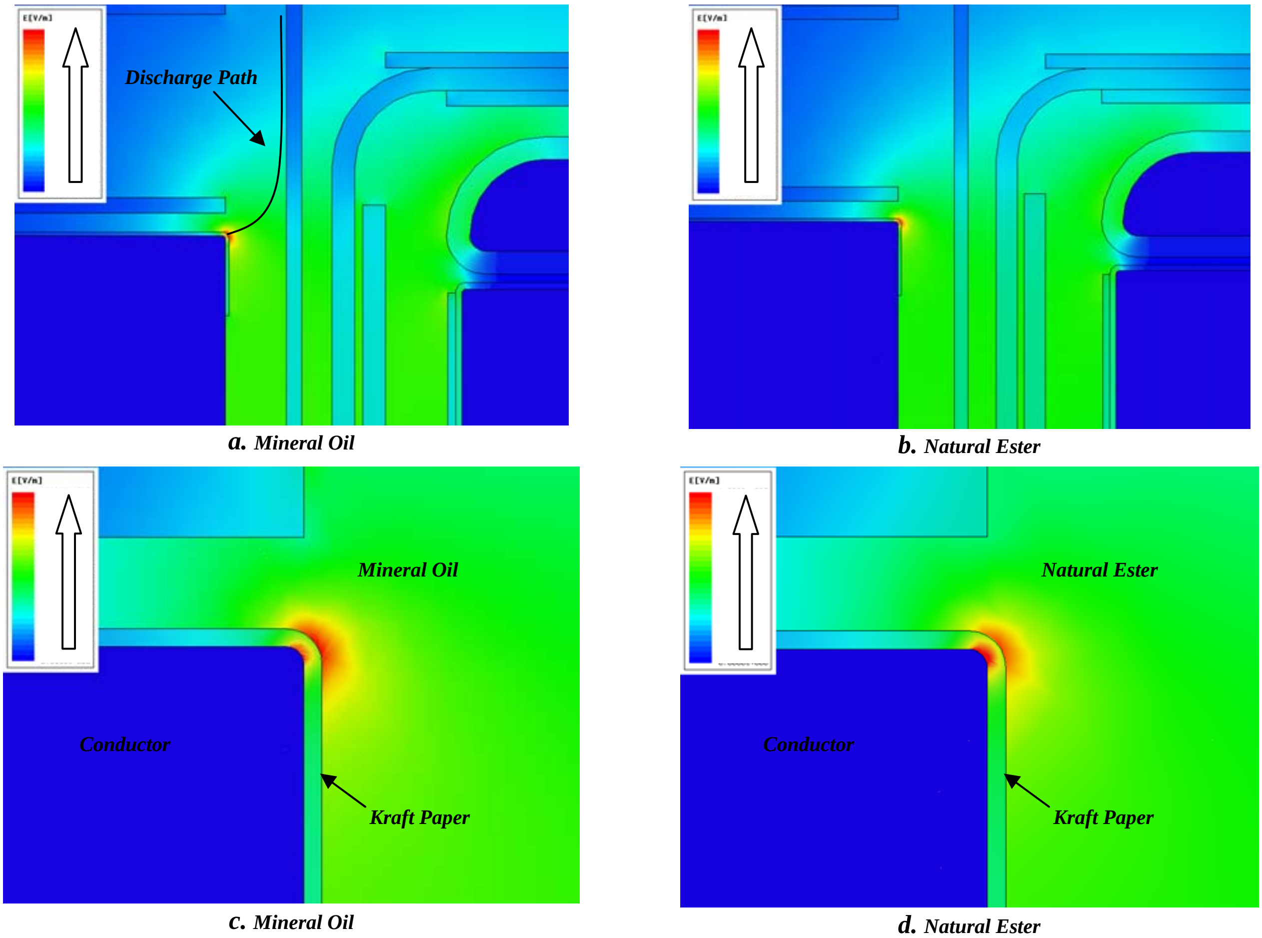

Fig. 3. Electric Field (kV/m) simulation for the highest stress point of a 69kV power transformer design in Mineral oil and Natural ester fluid.

Figure 4 presents the voltage stress along the discharge path shown in fig 3a.

The initial of the discharge path is the interface between paper and oil and at this point, a difference of 10% in electric field for both fluids is shown in fig. 4.

The electric field in the beginning of the discharge, as observed from simulation results, is lower for natural ester fluid.

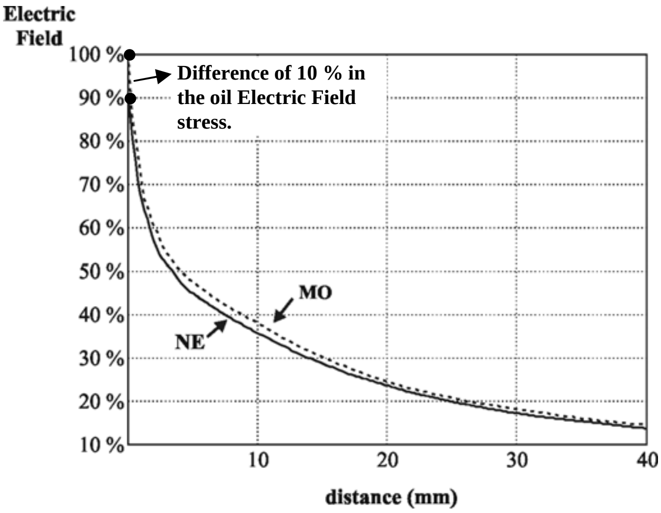

Fig. 4. Electric Field along the discharge path for mineral oil (MO) and Natural ester fluid (NE).

III. Three Phase 69 kV Prototype

The 69 kV prototype is a three phase transformer. The design of all three phases was done considering the same dielectric distances and composition between solid and liquid insulation.

All phases have been tested under impulse voltage test using the same voltage steps.

An oil sample was collected before to initiate the laboratory experiments and all gases and chemical properties was checked to certify the oil conditions.

Some of the results obtained, in the analyses, are presented in table I.

TABLE I
NATURAL ESTER FLUID SAMPLE PROPERTIES

Property	Unit	Value
Density@20ºC	kg/dm^3	0.9190
Dissipation Factor@25ºC	%	0.02
Water Content	mg/kg	8.5
Dielectric Breakdown (IEC 60156)	kV	70.6

The rising-voltage method is used for the dielectric tests with an increasing rate of 5% of the BIL voltage between each test. For each tested voltage three full waves and two shopped waves was applied.

The design for the 69 kV prototype is the same commonly employed for transformers manufactured in mineral oil. The results obtained in natural ester fluid were as follows:

Phase A: Failed at the first full wave impulse applied (100 % of the design BIL);

Phase B: This phase has passed twice to all tests in 100 % of the BIL and has a failed in the first full wave applied at 110%;

Phase C: Have passed to 2 shopped waves with 110% of the BIL and have failed to the second full wave applied in 100%.

After the results described above, the prototype was repaired and some changes in the original design was done in order to adequate the final project to the natural ester fluid.

Phases A and C have the same dielectric design in the new project, but phase B has some differences in the design conception.

In the new impulse test realized, according to the same procedure employed before, phase B has been approved with 130% of the design BIL and phase C has failed to the second full wave applied in 105%. Phase A is not tested because once it has the same design of phase C it has been let to be tested in mineral oil.

Once the tests were finished with Natural ester fluid, the transformer was refilled with mineral oil which has the chemical characteristics as shown in table II.

TABLE II
MINERAL OIL SAMPLE PROPERTIES

Property	Unit	Value
Density@20ºC	kg/dm^3	0.8848
Dissipation Factor@25ºC	%	-
Water Content	mg/kg	4.2
Dielectric Breakdown (IEC 60156)	kV	71.5

Tests in mineral oil were performed using the same methodology described before and all phases have passed to 115 % of the BIL, even for phase C that has its solid insulation already damaged for previous tests in natural ester fluid.

IV. Single Phase 245 kV Prototype

A single Phase prototype was tested dielectrically in natural ester fluid.

Finite elements analyses were performed before to start the laboratory tests in order to identify critical points of the design in terms of probability of discharge.

Figure 5 presents the electric field on the center discs of the high voltage (HV) winding and the discharge path of the failure occurred during laboratory tests. It has to be considered that the HV winding is a center connection coil and the stress voltage during the impulse voltage test distributes, mainly, capacitively along the winding discs.

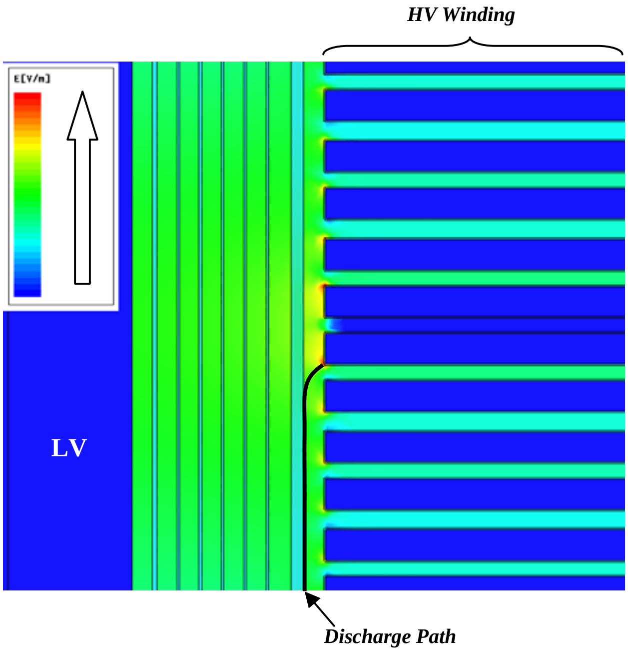

Fig. 5. Electric Field in the center of the high voltage winding.

An oil sample of the prototype was obtained before the beginning of the electrical tests. The dielectric breakdown was measured to be 72.5 kV (according to IEC 60156) and the water content 15.3 mg/kg.

The first design approach was done employing the same insulation perspective used for mineral oil. Considering this situation the prototype have failed in the voltage of 100 % of the designed BIL in a long gap discharge path, as shown in fig. 5. The startup location of the streamer is shown in fig. 6.

Fig. 6. The location of the streamer initiation on the high voltage winding.

V. Discussion

According to the design curves for mineral oil presented in [17], a safe margin of around 15 % is expected at the point of failure for the 230 kV prototype.

In both prototypes the discharge takes place in natural ester for creep distances higher than 150 mm.

Streamer propagation and breakdown characteristics of natural ester fluid are under study in the literature. In [13], the streamer propagation velocity in natural ester was measured for negative and positive polarities.

There are observed some difference in the streamer propagation velocity in natural ester fluid compared to mineral oil. This variation was supposed to impact on the results observed in both prototypes.

Once a high intensity nonuniform electric field is able to produce the inception for the discharge it propagates in a higher velocity in natural ester fluid compared to mineral oil.

Higher propagation velocities may reduce the dielectric supportability considering nonuniform fields and long gap distances in natural ester fluid.

VI. Conclusion

Previous papers presented in the literature pointed to some similarities and differences in the dielectric characteristics of natural ester fluid compared to mineral oil.

However, It has to be considered that all dielectric tests previous published evaluate one characteristic of the insulation fluid each time.

This study presents two prototype transformers tested in the as built condition of the equipment.

The experimental tests have shown some differences in the design perspective of both insulation fluids (mineral oil and natural ester fluid). Differences were observed mainly in the presence of nonuniform fields and long gap distances.

The observed differences, in any case, do not mean that high-voltage power transformers may not be design and manufactured in natural ester fluid. It just implies that the design characteristics of high voltage equipments in natural ester are different from the commonly used for mineral oil.

VII. References

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