http : //www.cigre.org

A2_203 2012 Paris Session

Considerations for the Design, Manufacture, and Retro – filling of Power Transformers with High Fire Point, Biodegradable Ester Fluids

J. HAJEK*, J. KRANENBORG
P. SUNDQVIST, R. JONSSON
T. SKYTT, B. SAMUELSSON
ABB
Sweden

R. ASANO JR
ABB
Brazil

G. K. FRIMPONG
R. GIRGIS
ABB
USA

SUMMARY

Because of a number of exceptional properties over mineral oil, ester fluids are now being used in more medium and large power transformers. At the same time, there are significant differences in the dielectric & thermal properties and other material parameters, between mineral oil and ester fluids, which need to be considered in the design, manufacture, retro – filling, and service of these transformers.

This paper presents results of investigations, calculations, and measurements made to identify the special material characteristics that need to be considered when designing the core and windings of these transformers. The paper also presents the factors that must be considered in the selection, design, and determination of the voltage and current ratings of bushings and tap – changers to be used in ester fluid – filled power transformers. In addition, the paper identifies properties of ester fluids that would require different procedures in the processing of the fluid during manufacture and impregnation of the solid insulation in the transformer.

The factors that should be considered when an old mineral oil – filled power transformer is to be retro – filled with an ester fluid are presented. These allow the transformer to benefit from the advantages of the ester fluid but not negatively impact its performance and reliability during future years of service. During transformer service, some oil quality parameters of ester fluids; such as power factor, acidity, interfacial tension, etc, do not reflect the same correlation to fluid dielectric or thermal performance as they do in mineral oil. Also, some diagnostic parameters which determine the condition of the solid insulation in a mineral oil - filled power transformers will need to be considered differently in relationship to the different properties of ester fluids.

Finally, the paper presents how the advantageous property of longer life of cellulose in ester fluids could be evaluated and benefited from, resulting in more optimized design of ester fluid – filled power transformers.

KEYWORDS
Ester fluids, Power transformers, Transformer Cores, Transformer windings, Transformer retro – filling, Transformer design

*jan.hajek@se.abb.com

1. Introduction

Ester fluids have been used successfully in distribution and traction transformers for many years. However, ester fluids have other qualities that prompt careful consideration when dealing with the higher voltages, power ratings, and size of medium and large power transformers. Issues that may not be important in smaller transformers become extremely important in the reliable design and application of ester fluids in power transformers. Moore [1] identified several performance characteristics of ester fluids that must be investigated before they are used in power transformers. The impacts of some of the significant characteristics are considered in the sections that follow.

2. Transformer Design Considerations

In designing medium and large power transformers with ester fluids, designers need to account for a number of significant differences in the properties, characteristics, and material parameters, between mineral oil and ester fluids. Design calculations and design rules for the dielectric and thermal performance of mineral oil – filled power transformers have been developed and continuously enhanced through extensive operating and testing experiences over the years. It is, therefore, critical for designing reliable ester fluid – filled power transformers that corresponding design calculations and design rules are developed based on theoretical, analytical, and experimental investigations, together with the experience gained from the many years of designing transformers filled with mineral oil. Presented in this section of the paper are results of investigations performed to develop such design guidelines and calculations for ester fluid – filled power transformers. Also presented in this section is how the different properties and characteristics of ester fluids would impact the design of the core and windings of these transformers as well as how that impact should be considered in designing these transformers in order to achieve the same or a better level of performance and reliability as that of mineral oil – filled power transformers. Factors that must be considered in the selection, design, and determination of the voltage and current ratings of bushings and tap – changers to be used in ester fluid – filled power transformers are presented in section 2.3.

2.1 Dielectric Design Considerations

In an insulation system composed of fluid and solid insulating materials, the distribution of electrical stress between the solid and liquid dielectrics is governed by the relative values of the dielectric constant of both the liquid and solid materials. The dielectric constants of ester dielectric fluids are typically higher than that of mineral oil and closer to the dielectric constant of pressboard and insulation paper. Because of the better match of the dielectric constants in an ester fluid/pressboard system, the disparity in distribution of stresses between solid and liquid is much lower than that in a mineral oil/pressboard system. One result of this is that partial discharge inception occurs at slightly higher voltage in ester-filled insulation systems than their mineral oil counterparts. Test results have also shown that for smaller insulation distances, the average breakdown voltage in ester fluids under both AC and impulse stress is similar. These findings would explain the successful application of ester fluids in distribution class transformers for more than a decade using the same dielectric guidelines as mineral oil.

Differences in dielectric performance between mineral oil and ester fluids are manifested at longer insulation gaps and depend also on electrode configuration. Flashovers in transformers are the result of streamers travelling the full length of distances between electrodes. The flashover phenomenon can be physically divided into two processes; namely, initiation and propagation, each with distinctive characteristics. From studies that have been done, it is clear the initiation process starts in regions of high electric fields, while propagation requires much lower local electric fields. It is now well understood that initiation of discharges is similar between ester fluids and mineral oil [2]. For this reason test methods that evaluate mostly the discharge initiation process are not adequate for highlighting the dielectric differences between mineral oil and ester fluids. As an example, the standard dielectric tests under uniform AC fields in small gaps require significantly higher fields for breakdown. Because of the high field and the short propagation distance, the initiation of the streamer and flashover would occur almost simultaneously. Consequently differences between ester fluids and mineral oil are not easily discernable. Moreover, such high fields are not realistic in actual transformer geometries which typically result in semi-uniform fields and non-uniform fields when there are particles present.

The main difference between the dielectric performance of ester fluids and mineral oil is in the propagation of streamers in non - uni form fields and especially in long gaps. With increasing gap length under non-uniform fields the breakdown voltage in ester fluids is lower than in mineral oil under impulse and AC stresses [3, 4]. Also, the acceleration voltage, which expresses the voltage at which a streamer transitions from "slow" event to "fast" event, is significantly lower in ester fluids than in mineral oil. Fast streamers are in general more dangerous due to the fact they travel much longer distances in the liquid at a short time interval and, thereby, increase the risk for a full electrical breakdown and possible failure in the transformer. Moreover, the transition from a slow to a fast streamer in ester fluids occurs at only a slightly higher voltage than the average breakdown voltage, whereas there is a large voltage difference between the average breakdown voltage and the acceleration voltage in mineral oil (Figure 1). The differences are more pronounced for positive streamers than for negative streamers under impulse voltages. The presence of pressboard barriers under impulse voltages significantly affects the acceleration voltage in mineral oil but have no effect in ester fluids.

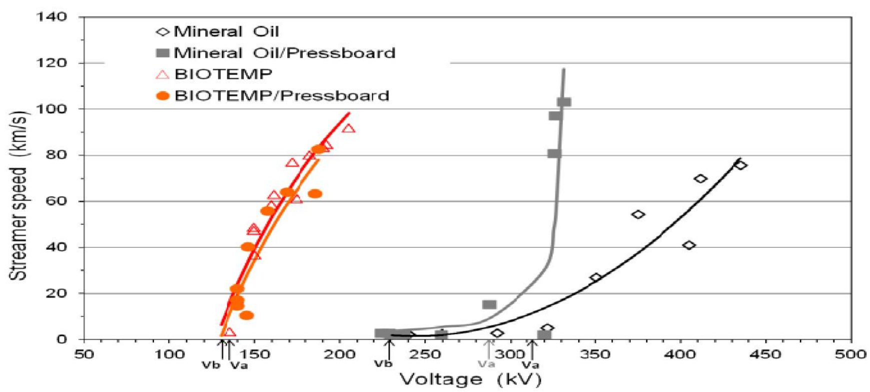


Figure 1 - Positive Streamer Velocity in Needle-Plane Geometry With and Without Pressboard Interface (Va = acceleration voltage, Vb = average breakdown voltage)

Differences in the dielectric behavior of mineral oil and ester fluids do not limit the use of ester fluids in high voltage power transformers. However, manufacturers must understand the implications of these differences and similarities on the transformer design and must address them with proper dimensioning rules. Failure to do so will increase the risk of dielectric failures of ester fluid – filled power transformers at test, or potentially in the field [5].

2.2 Thermal Design Considerations

Because of the appreciably higher viscosity of ester fluids compared to that of mineral oil, the flow of ester fluids through the windings, core, and cooling equipment is lower than that of mineral oil, leading to a relative increase of top oil, windings, and core temperatures. At the same time, ester fluids have higher thermal conductivity and slightly higher heat capacity than mineral oil. However, these better thermal properties only slightly compensate for the negative impact of the higher viscosity of ester fluids [6] in medium and large power transformers; where heat transport is mainly governed by convection. It is, therefore, necessary to:

(1) Optimize the design of the windings, core, and cooling system to improve the thermal dynamics of ester fluids in the transformer

(2) Improve the cooling efficiency of the cooling system for ester fluids.

This is only possible by performing proper modeling of the thermal dynamics of ester fluids in the windings, core, and the cooling equipment. This section of the paper presents a number of thermal design considerations examined to achieve a reduction of the negative impact of ester fluids on core and windings temperatures.

2.2.1 Thermal Design Considerations of the Core

The impact of ester fluids on the core hot spot and surface hot spot temperatures in a power transformer is determined by:

1. Effective heat transfer coefficient of the fluid in the cooling ducts as a consequence of the cooling duct geometry as well as the fluid's thermal conductivity and viscosity
2. Thermal conductivity across the core – stack with the ester fluid being the conducting medium between the laminations.
3. Impact of the ester fluid on the temperatures of the tank top & bottom oil as well as its impact on the temperature of the fluid at the top of the windings.

In order to accurately predict the impact of ester fluids on core temperatures, rigorous thermal modeling was performed to evaluate the above effects. In Table 1 below, calculated temperature gradients of the hot spot and surface hot spot of the core (above temperature of the surrounding fluid) of a 50 MVA transformer are compared to measured values when the transformer was tested at 110 % over-excitation at no load. The table demonstrates good agreement between measured and calculated core temperature values. In Table 2, calculated values of the impact of ester fluids on the core temperature gradients are compared with the measured values at no load.

Table 1 – Calculated vs. measured core temperature gradients at no load, ºC

		Hot Spot	M - C	Surface	M - C
Mineral Oil	Calculated	29.4	**-2.3**	18.1	**-1.4**
	Measured	27.1		16.7	
BIOTEMP	Calculated	35.5	**-0.5**	24.4	**-1.4**
	Measured	35.0		23.0	

Table 2 – Calculated vs. measured impact of ester fluids on core temperatures at no load, ºC

		Hot Spot	Surface
(BIOTEMP - Mineral Oil)	Calculated	**6.1**	**6.3**
	Measured	**7.9**	**6.3**

Using the same modeling technique, the impact of ester fluids on the core hot spot and core surface hot spot gradients was calculated for cores with different diameters, materials, flux densities, and different number of cooling ducts when the transformer is operating at full load. Sample results of these calculations are presented in Table 3 below for a core with 3 cooling ducts. As expected, the greatest impact is on the inner part of the core between ducts.

Table 3 – Calculated impact of ester fluids on temperature gradients of a 3 – duct core, ºC

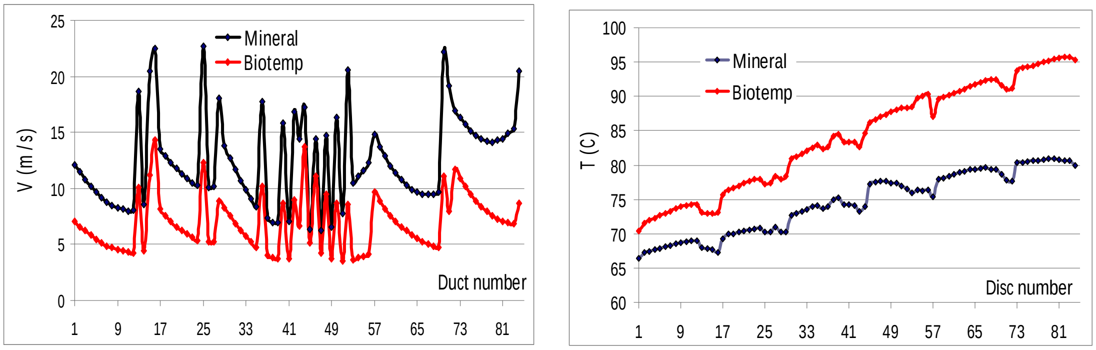
Core Hot Spot		Surface
Inner Part	Outer Part	Hot Spot
11.7	3.8	6.5

From above, it is evident that one needs to develop accurate calculation of core hot spot and core surface hot spot gradients for ester fluid – filled transformers. Also, when designing the core of these transformers, one should consider ways to reduce these temperatures (when needed), using the developed calculations and optimizing core and cooling design parameters affecting core temperatures.

2.2.2 Thermal Design Considerations of the Windings

The impact of ester fluids on the windings average and hot spot temperatures in a power transformer is mainly determined by velocities of the fluid in the windings, winding duct dimensions, and impact of the ester fluid on the temperature differential of the tank oil. In order to accurately predict the impact of ester fluids on winding temperatures, rigorous thermal modeling was made to evaluate above effects.

Figure 2 (a) below presents calculated fluid velocities in the horizontal ducts of the LV disc winding of a medium size power transformer, when filled with mineral oil and when filled with an ester fluid, at full load. The figure demonstrates much reduced velocities of the ester fluid as well as much more significant drops in the fluid velocity within individual winding sections between oil – guides. This translates into higher winding temperatures and a much larger temperature difference between the top and bottom winding temperatures as demonstrated in Figure 2 (b). This causes the winding hot spot to be significantly higher for ester fluid – filled power transformers.



(a) Fluid velocities in horizontal ducts (b) Temperatures of discs of winding

Figure 2: Calculated fluid velocities and temperatures in a disc winding of a power transformer

From above, it is evident that one needs to develop accurate modeling of the whole thermal circuit of the cooling system, tank oil, and windings for ester fluid – filled transformers and to use such a model in optimizing the design of the windings of these transformers in such a way as to reduce the oil and winding temperatures to meet the guaranteed levels.

2.3 Design Considerations of Bushings and Tap – Changers

It is easy to overlook the need for examining transformer accessories in ester applications. This is due to the typical focus on only the transformer itself, no matter whether the installation is new or retrofit of an existing unit. All accessories, especially bushings and tap changers (both on-load and de-energized), need to be tested and verified to assure proper dimensioning and functioning in ester fluid applications.

The fluid in a tap-changer does not only cool and insulate, but also quenches arcs and lubricates mechanical moving parts. Depending on the type of tap-changer, the stresses it is exposed to differ in severity and magnitude. If the tap-changer is an in-oil arc quenching type, the tap-changer should be equipped with an oil filtering unit. During tap-changing operations, the arc decomposes the oil during the quenching process. The residues of this process are soot and moisture which remain in the oil. The time of soot sedimentation is longer, while the moisture absorption is higher for ester fluids when compared to mineral oils. If an in-oil arc quenching type tap-changer is used, it is important not to allow oxygen and moisture to enter the tap - changer compartment but to allow the arcing gases to escape. If tap-changers with vacuum technology are used, this requirement may not be necessary.

Bushings are rather critical in terms of flash-over distances when using ester fluids. The differences in behavior with regards to streamer velocity, stop length, etc. in combination with the electrical field around the bushing, make it necessary to change the design criteria for bushings above distribution voltage levels.

Also, the viscosity of ester fluids is generally higher than that of mineral oil. However, it is very high at low temperatures and decreases significantly at operating temperatures. Thus, it makes it necessary to gain full understanding of the dielectric and thermal performance of the ester fluid – filled HV bushings across the whole range of the fluid temperatures. In this context, it is worth noting not only the lightning impulse behavior differs between esters and mineral oil, but also the AC behavior shows a different pattern in ester fluids compared to mineral oil at transmission voltages [4].

3. Considerations in Manufacturing of Ester Fluid – filled Power Transformer

Manufacturing power transformers with ester fluids demands some different processes and quality criteria. In order to ensure good quality of the fluid in service, it is necessary to ensure all materials that are in contact with the fluid are compatible; e.g., the materials do not leach ionic contaminants into the fluid or react in some fashion with the fluid. Most common materials used in transformers (copper, steel, aluminum, cellulose, etc) are compatible with ester fluids. Some rubbers may, or may not, be compatible with some ester fluids depending on the composition of the filler materials used in the rubbers. It is, therefore, important to check samples of rubbers that may come in contact with the fluid using the ASTM method D 3455 [7], but with the aging done in a nitrogen atmosphere. This includes gaskets, conservator bags, oil delivery hoses, and under oil components. If ever in doubt about a material, it is recommended to check its compatibility.

Because of the higher affinity of ester fluids to moisture, it is necessary to limit exposure of the oil to the atmosphere during the manufacturing process as well as during operation. In addition, some ester fluids exhibit poor stability to oxidation. For these reasons, ester fluid – filled power transformers are typically constructed with a sealed nitrogen blanket or a constant oil pressure system with a bag (sealed COPS).

Again, because of the higher viscosity of ester oils compared to mineral oil, impregnation of cellulose structures occur at a slower rate [8]. Improper impregnation of cellulose can leave trapped air bubbles in the solid insulation, which can generate partial discharges or even insulation breakdown during dielectric testing. It is, therefore, important to perform simulations and tests to find adequate impregnation time before the transformer is subjected to any dielectric tests.

Small amounts of mineral oil in an ester fluid can reduce the flash and fire points of the ester fluid. On the other hand, fractional amounts of ester fluid in mineral oil, increases the charging tendency of mineral oil beyond its acceptable limits. Therefore, it is important to ensure as little cross contamination of oils as possible if both mineral oil and ester fluid are delivered to the transformers using the same processing equipment.

4. Considerations in Retro – filling and for Transformer Service

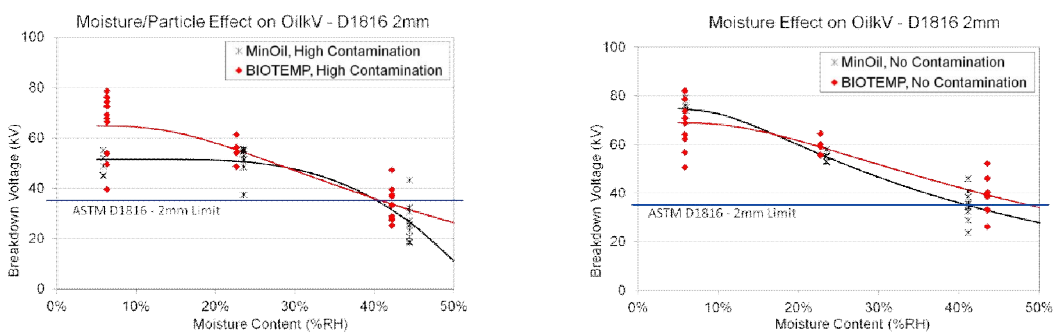
For a number of reasons that range from environmental benefits to reduction in the insurance premium, ester fluids have been used to retro – fill transformers already in operation. Retro – filling of power transformers requires qualified engineering assessment as there would probably need to be design considerations to accommodate the differences between mineral oil and other fluids [9]. When the details of the transformer design from the OEM is available, one can apply the knowledge, tools and rules developed for designing new ester filled transformers to exactly predict the performance of the transformer retro – filled with the new liquid. However, the design information is typically confidential and not readily available. In such a case engineering judgments must be made to estimate the performance of the transformer when filled with the ester fluid. One possibility, for example, is to use the data from the factory tests to estimate the internal heat flow distribution among the windings and predict the impacts of the different liquid properties in the winding and liquid temperatures.

Before retro – filling it is also important to verify the condition of the transformer as well as the reliability of the previously installed components. Oil analysis and additional field tests are required with this aim and also to provide a new basis for future monitoring and maintenance of the transformer. The fluid exchange process needs to be well controlled in order to minimize the volume of residual mineral oil in the transformer. Although mineral oil and esters are fully miscible, too much residual mineral oil can reduce the fire safety characteristics of the ester fluid.

Regarding maintenance and diagnostics, the requirements of the fluid for satisfactory performance of a transformer under test or during its lifetime are the same for ester fluids and mineral oil. However, some parameters that have direct impact on the performance of mineral oil in a transformer show little significance for ester fluids. For example, whereas increasing power factor of mineral oil has a direct relationship to decreasing dielectric breakdown strength, no such correlation exists for ester fluids. The same is true for acid neutralization number. Similarly, interfacial tension is used to determine the presence of polar contaminants in mineral oil [10]. Since ester fluids are composed of polar molecules, the effectiveness of interfacial tension become less significant. Therefore, it is important for users to understand what parameters directly impact the thermal and dielectric performance of ester fluids and to monitor these. For ester fluids, the most important parameters are the relative humidity which directly impacts the breakdown strength and the viscosity which directly impacts the thermal performance of the transformer. If other parameters are measured, it should be noted that their thresholds for diagnostics will be significantly different from those of mineral oil.

The conductivity (inverse of resistivity) of ester fluids is roughly two orders of magnitude higher than that of mineral oil. So, naturally the resistance of dry cellulose impregnated with ester fluids is lower than that impregnated with mineral oil. For this reason, the typical minimum insulation resistance values and also the temperature correction factors established for mineral oil systems are not applicable to ester impregnated systems. A different set of diagnostic rules for insulation resistance measurements would need to be applied for transformers filled with ester fluids.

On the other hand, breakdown voltage is an important characteristic to be monitored. The dielectric breakdown strength of the fluid determines its ability to withstand the electrical stresses imposed on it during testing and under various operational and fault conditions during its service life. Of particular importance is the effect of moisture, particulates and service life on the dielectric breakdown strength of the oil. With regards to moisture, it has been demonstrated that the deterioration of breakdown strength is best expressed in terms of the relative saturation of moisture than the absolute water content. Measurements were made on a high oleic natural ester fluid to check the effect of both moisture and particle contamination on the breakdown voltage. The effect of moisture and contamination with no contamination and at high level of contamination (maximum count in 100ml of 5µm size copper particles = 130,000 and maximum count of 20µm size particles = 16000) is shown in Figure 3. Other researchers have obtained similar results with other ester fluids [11]. The results show there is no adverse effect on breakdown strength when mineral oil is substituted with ester fluids and the same oil breakdown limits already set for mineral oil are applicable to ester fluids.



a) with Cu contamination b) without contamination

Figure 3 - Effect of Moisture and Particles on AC Breakdown (ASTM D1816 - 2mm Gap)

A change in viscosity caused by the ageing of the liquid is also important to be monitored because it can affect the performance of the cooling system, especially in power transformers. The fatty acid compositions of natural ester fluids determine their long term stability to heat, oxygen and light exposure. One of the markers of degradation of ester fluids is an increase in viscosity [12,13] and the production of stray gases at low temperatures (typically hydrogen and ethane). Depending on the application, it may be necessary to consider the effect of heat, oxygen or light (ultraviolet and infrared) on the viscosity of the selected ester fluid.

Ester fluids produce the same types of gases under the same fault conditions as mineral oil, but in different concentrations. The same analysis methods used to interpret dissolved gases in mineral oil transformers apply also to transformers filled with ester fluids. However, the limits on concentrations and ratios of fault gases used in these methods must be adapted for the selected ester fluid [14]. If the selected fluid is prone to stray gassing, this fact should be considered in the interpretation rules [15].

5. Considerations for Transformer Operation

The benefit of paper life extension in ester fluids has motivated several researchers to quantify and investigate its origin as well as to evaluate its potential in the design and manufacturing of power transformers [16,17,18,19]. Another way to quantify this benefit is by means of the temperature increase for the equivalent life expectancy. Recent measurements show a temperature advantage of at least 20°C for natural-ester impregnated cellulose insulation [20]. Based on this data, upper temperature rise limits for natural-ester-filled power transformers could be selected up to the values from the Table 4 below:

Table 4: Proposal for IEC temperature rise limits in transformers filled with natural ester

Top liquid temperature rise (K)	90
Average winding temperature rise (K)	80
Hot-spot temperature rise for solid insulation (K)	95

In this case, transformers filled with natural esters could be more compact when designed for continuous operation at higher temperatures or add important flexibility in the operation when loaded above the nameplate for ester – filled transformers specified for conventional temperatures.

6. Conclusions

Presented in this paper, are results of investigations, calculations, and measurements made by the authors of the paper to identify the factors that need to be considered in the design & manufacture of ester fluid – filled power transformers as well as in retro – filling of old mineral oil – filled transformers with ester fluids.

Here are some of the more important conclusions presented in the paper:

1. Differences in the dielectric behavior of mineral oil and ester fluids emerge in non-uniform fields and in large insulation gaps. The main difference is in the propagation behavior of streamers, where transition to fast events occur more rapidly and at lower voltages in ester fluids than in mineral oil. In designing high voltage ester fluid – filled transformers, implications of these differences must be addressed with proper dimensioning rules.
2. Ester fluids generally have higher viscosity than mineral oil in the typical operating temperature range. This does not significantly affect the thermal characteristics of smaller transformers, but have a significant impact in larger transformers. The impact of this higher viscosity is increased hotspot and surface temperatures of the core, lower oil velocities in the windings, larger temperature differences between top and bottom of the windings, higher top winding oil temperatures, and significantly higher winding hotspot temperatures. Therefore, in designing these transformers, one needs accurate models of the whole thermal circuit of the transformer in order to have an appropriate selection of the design parameters of the core and windings to ensure that all temperatures meet the guaranteed levels.
3. Because of the differences in dielectric and thermal behavior between ester fluids and mineral oil, it is necessary that all accessories, especially tap changers (both on-load and de-energized) and bushings, be tested and verified to assure proper dimensioning and functioning in ester fluid applications.
4. During manufacturing, proper handling procedures should be observed in order to avoid excessive exposure of the fluid to the atmosphere and contaminants. It is also important to ensure proper impregnation of all solid insulation structures in the transformer.
5. When an old mineral oil – filled power transformer is to be retro – filled with an ester fluid, a qualified engineering assessment should be performed so as to allow benefiting of the advantages of the ester fluid but not negatively impact the performance and reliability of the transformer. During operation, some oil quality parameters (e.g. power factor, acidity, interfacial tension) do not reflect the same correlation to the condition of the ester fluid. Also, some diagnostic parameters that determine the condition of the insulation in a mineral oil - filled power transformers will need to be considered differently in relationship to the special properties of ester fluids.

BIBLIOGRAPHY

1. H. Moore, "Requirements and Expectations for Natural Ester Fluids for Application in Power Transformers", IEEE Transmission and Distribution Conference and Exhibition, pp. 23-24, 2006
2. A. Eriksson, L. Rongsheng, C. Tornkvist, "Differences in Streamer Initiation and Propagation in Ester Fluids and Mineral Oil", Paper #40, IEEE ICDL, Trondheim, Norway, 2011
3. L. Rongsheng, C. Tornkvist, V. Chandramouli, O. Girlanda, and L. A. A. Pettersson, "Ester Fluids as Alternative for Mineral Oil: The Difference in Streamer Velocity and LI Breakdown Voltage," IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Virginia, US, pp. 543-548, 2009.
4. P. Jarman et al, "Electrical Performance of Ester Insulating Liquids for Power Transformers", Paper PS2-O-5, CIGRE SC A2 & D1 Joint Colloquium, Kyoto Japan, 2011
5. T. B. Marchesan, A. J. Fanchin, "Natural Ester Fluid: The Transformer Design Perspective", IEEE Transmission and Distribution Latin America Conference, São Paulo, 2010
6. R. Girgis, M. Bernesjo, G. Frimpong, "Detailed Performance of a 50 MVA Transformer filled with a Natural Ester Fluid versus Mineral Oil", Paper A2-107, CIGRE Conference, Paris, 2010
7. ASTM D3455 - 11 Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin
8. J. Dai, Z. D. Wang, "A Comparison of the Impregnation of Cellulose Insulation by Ester and Mineral oil", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 15, No. 2, pp. 374-381, April 2008
9. CIGRE Working Group A2-35, "Experiences in Service with New Insulating Liquids", Brochure 436, Paris, 2010
10. R. Asano, C. Claiborne, S. Singha, "Diagnostic Methods for Bio-degradable Oils", CIGRE Session Group Ref. :D1, Pref. Subject : PS2, Question N° :2.4, Paris, 2010
11. X. Wang, Z. D. Wang and J. Noakhes, "Motion of Conductive Particles and the Effect on AC Breakdown Strength of Ester", Paper #87, IEEE ICDL, Trondheim, Norway, 2011
12. L. Lewand, C. Claiborne, D. Cherry, "Oxidation And Oxidation Stability Of Natural Ester Dielectric Liquids", Paper IM- Doble Client Conference, Boston, 2010
13. J. Viertel, K. Ohlsson, S. Singha, "Thermal Aging And Degradation Of Thin Films Of Natural Ester Dielectric Liquids", Paper #128, IEEE ICDL, Trondheim, Norway, 2011
14. G. K. Frimpong, TV Oommen, C. C. Claiborne, "Interpretation of Dissolved Gases in High Oleic, High Fire point Ester Dielectric Fluids", Paper PS2-P-7, CIGRE SC A2 & D1 Joint Colloquium, Kyoto Japan, 2011
15. I. Atanasova-Hoehlein, "Influence of Oxidation Stability of Insulating Fluids on the Diagnostic Interpretation of Transformer Condition", Paper PS1-O-12, CIGRE SC A2 & D1 Joint Colloquium, Kyoto, 2011
16. N. Azis and Z. D. Wang, "Acid Generation Study of Natural Ester", XVII International Symposium on High Voltage Engineering, Hannover, 2011
17. R. Liao et al., "A Comparative Study of Physicochemical, Dielectric and Thermal Properties of Pressboard Insulation Impregnated with Natural Ester and Mineral Oil", IEEE Transactions on Dielectrics and Electrical Insulation Vol. 18, No. 5; October 2011
18. M. Hrkac, et al., BIOTEMP® Transformer Technology for Innovative Compact Substation, 7th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion, Cyprus, 2010
19. R. Asano et al., "Development of New Hybrid Insulation System using Natural Ester Fluids", CIGRE SC A2 & D1 Joint Colloquium, Kyoto, 2011
20. G. Frimpong, TV Oommen, R. Asano, "A Survey of Aging Characteristic of Cellulose Insulation in Natural Ester and Mineral Oil", IEEE Electrical Insulation Magazine, Vol. 27, No. 5, pp. 36-48, Sep/Oct 2011