CIGRE-229 **2019 CIGRE Canada Conference**
Montréal, Québec, September 16-19, 2019

Preliminary Study of Ester-based Fluids for Application in Transformers Serving in Cold Climatic Regions

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SUMMARY

Using ester-based oils in transformers operating in cold climatic regions remains challenging. It is known that oil viscosity increases with lower temperatures, hampering oil circulation through cooling ducts. This could cause internal transformer temperatures to increase and lead to hazardous situations. Thus, new oils must have very low pour points to withstand transformer operation even in the extreme cold. The purpose of this work is to perform preliminary tests on a novel synthetic ester-based oil that has a very low pour point of -75°C. Its main objective is to assess the feasibility of using a very low pour point ester fluid in transformers operating in cold regions. For comparative purposes, a synthetic ester with a pour point of -56°C, a natural ester based oil with a pour point of -31°C and a mineral oil were also considered. The selected oils were subjected to accelerated thermal aging in the presence of cellulose insulation and a copper catalyst at 150°C for six weeks. Diagnostic measurements, including particle count, turbidity, and ultraviolet visible spectroscopy (UV/Vis), were carried out after every two weeks of thermal stressing to understand the rate of thermal degradation of the insulating fluids. The change in viscosity of non-aged and aged oils (6 weeks) was also reported at different temperatures ranging from -35°C to +20°C. Preliminary results on the degradation and physicochemical properties of this very low pour point liquid are presented and discussed. It was observed that the degradation behaviour of the low pour point liquid is similar to that of the other synthetic ester that has a pour point of -56°C.

KEYWORDS
Degradation, ester oil, insulation oil, transformers, low temperatures.

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INTRODUCTION

Traditionally, mineral insulating oils have been used in transformer insulation technology for insulation and cooling purposes. With the advent of green technology and increasing technical demands, utilities and engineers have turned their attention to alternative insulating fluids for use in transformers. In the search for alternatives to mineral insulation oils, ester-based dielectric fluids have been found to be potential replicates. They are gaining wide popularity as alternative candidates for use in high-voltage insulation systems. Some of the thermal and dielectric properties of these new oils have been found to be superior to mineral oils. They have also been found to have a high degree of compatibility with other materials in transformers. With the application of these oils to transformer insulation, the rate of degradation of oil-paper insulation, technical benefits, and maintenance costs have been found to be much better than with mineral oils [1]. Using these new oils in transformer insulation technology has been a topic of research in recent years. Several studies from around the globe have confirmed the suitability of these oils for transformer insulation and cooling purposes [2, 3]. Others have revealed that the dielectric (high dielectric strength) and thermal (high fire point) performance of ester fluids is better than that of the existing mineral oils [4, 5].

The application of natural esters has been limited to sealed transformers due to their poor oxidation stability, which can result in gelling over time [6, 7]. The viscosity of these ester fluids presents another challenge as they exhibit a higher kinematic viscosity than mineral oils. Thus, these new fluids may cause deficiencies and require suitable changes in cooling systems [8]. In addition, the limited availability of diagnostic and prognostic test methods for maintaining ester-filled transformers is also a potential concern for condition monitoring engineers. More importantly, new oils often require active part redesigns (thermal and dielectric)—retro-filling must be carefully assessed by the transformer manufacturer. However, ester-based insulating fluids have been found to have a good compatibility with cellulose insulation in aiding the longevity and dielectric integrity of the solid insulation [8, 9].

Nevertheless, the use of these new oils in cold climates requires investigation. Hence, a study of the behaviour of ester fluids at extreme low temperatures and cold starts of ester-filled transformers would be of great interest to utilities that operate in cold countries. To the best of the authors' knowledge, there is very little published literature on the topic "cold start of ester filled transformers" [10]. It is known that temperature has a significant impact on the physicochemical and dielectric properties of transformer insulation oil. Of the properties of insulation oil, pour point—the temperature below which oil increases in viscosity to the point where it can no longer flow—is a critical parameter in cold regions. Oil fluidity is an important parameter in ensuring the functionality of oil as a coolant. Hence, in this study, a very low pour point ester-based fluid was investigated to study its thermal degradation behaviour. The main objective was a preliminary assessment of a novel low pour point ester-based fluid for applications in transformers operating in cold regions. This low pour point fluid was subjected to accelerated thermal stresses, and some diagnostic characterizations are reported in comparison to synthetic esters, natural esters, and mineral oil.

EXPERIMENTAL

For this study, mineral oil (MO), synthetic ester (SE1), natural ester (NE) and a very low pour point synthetic ester-based fluid (SE2) were thermally aged in the presence of cellulose insulation and a copper catalyst. Even though natural esters are 'not recommended' for breathing transformers due to their lower oxidation stability, all the fluid samples were submitted to oxidative thermal aging with a view to understanding comparative oxidation stability. Accelerated thermal aging is faster than real-time aging and provides samples with a controlled thermal history. The fluids, as received from the manufacturers, were subjected to thermal stressing with 1:10 ratio of cellulose insulation (standard Kraft paper) and 3 g/L of copper. The thermal aging used a modified method based on ASTM D1934 at 150°C for six weeks with a controlled thermal aging history at 2 weeks, 4 weeks, and 6 weeks. To better understand the deterioration of oils and expedite the aging process, the aging factors adopted for this study allowed the oils to reach degradation in the early stages of the experiment. These accelerated aging factors were also selected to observe the long-term degradation behaviour of oils on a comparable scale. It should be mentioned that the oil/paper insulation was aged in an unsealed environment in a mechanical convection oven. For every 2 weeks of thermal aging, ultraviolet visible spectroscopy, turbidity, and particle count measurements were performed to evaluate the oxidative degradation of the oils. To investigate the fluidity of SE2 at low temperatures, viscosity measurements were performed at temperatures ranging from -35°C to +20°C.

RESULTS AND DISCUSSION

Viscosity

The viscosity of the oils at different temperatures was measured to understand their respective fluidity. The temperatures identified for measurement ranged from -35°C to +20°C. The change in viscosity of both mineral and esters oils over thermal aging was assessed. The viscosity of non-aged and aged oils (after 6 weeks) is presented in Figure 1.

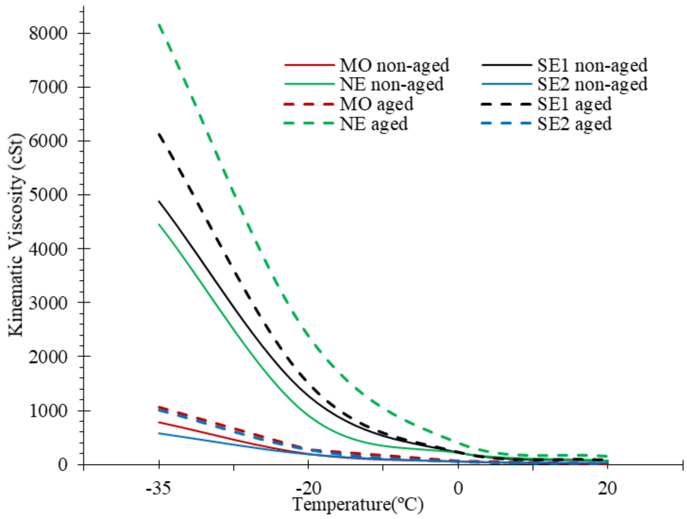
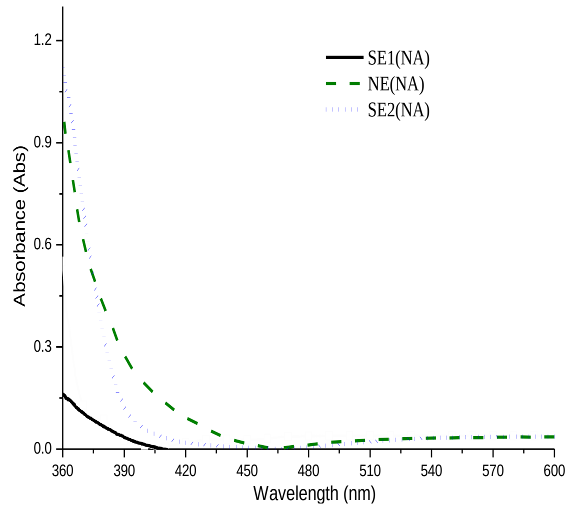


Figure 1. Variation in viscosity for non-aged and 6-week aged oils at different temperatures.

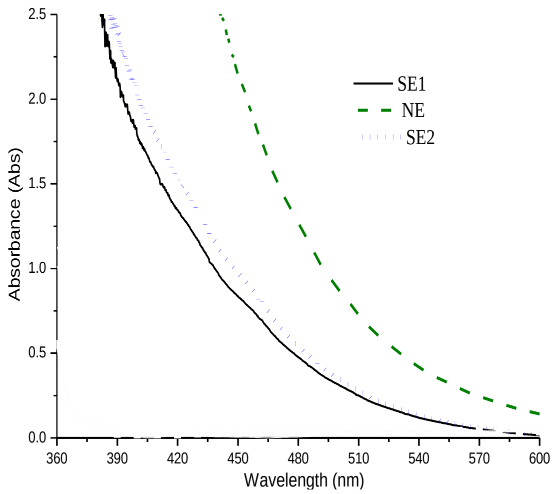
The oxidation of insulating fluids produces large molecular weight compounds leading to the increase of oil viscosity. These results agree with the aging setup because the experiment was conducted in an unsealed environment. It is known that ester fluids have a high viscosity and hence the viscosity of synthetic esters and natural ester fluids is higher for non-aged and aged oils. For the tested fluids, oxidation led to an increase in the viscosity with more impact on NE as expected. The viscosity of SE2 was found to be lower than SE1 and NE and is similar to mineral oil.

Ultraviolet Visible Spectrophotometer

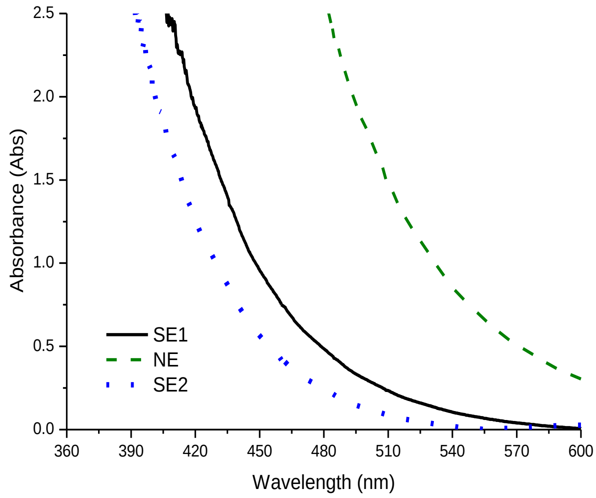
For every two weeks of thermal aging, oil samples were subjected to ultraviolet visible spectrophotometer (UV/Vis) analysis to understand the deterioration of oils. The ASTM D6802 standard test method was adopted to perform and analyze this measurement. It is to be mentioned that the ASTM D6802 test method is applicable to mineral insulating oils only. Spectral curves of mineral oil are not presented here to avoid a direct comparison of ester fluids to mineral oils. However, this method was adopted to monitor the absorption and decay products of ester fluids at different wavelengths. In transformer insulating oil, oxidation products are evident with aging and accordingly the absorbance and transmittance of light varies. It is known that with an increased concentration of decay contents, absorbance of oil to light increases proportionally. Hence, the spectral curve tends to shift towards higher wavelengths as oil age increases. The area under such a spectral curve is directly related to the concentration of dissolved decay contents in oil [11, 12]. The spectral curves of NE, SE1, and SE2 with aging time and non-aged (NA) are presented in Figure 2. Results and the meaning of the test are different between the fluids but reflect the degree of degradation and possible contamination during aging. Authors used a UV-VIS spectrometer that is capable of measuring absorbance at different wavelengths in a single measurement scan to obtain the absorbance from 360-600 nm.



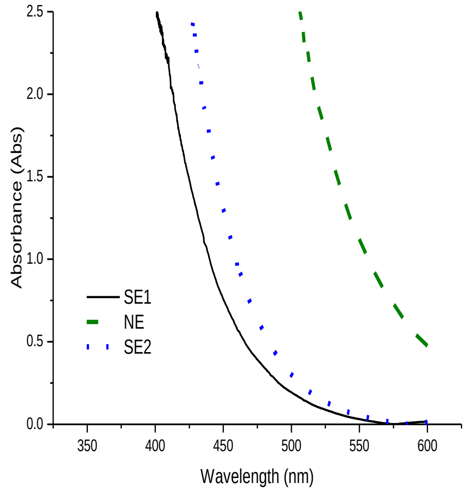
(a) Spectral curves of Non-Aged (NA) oils



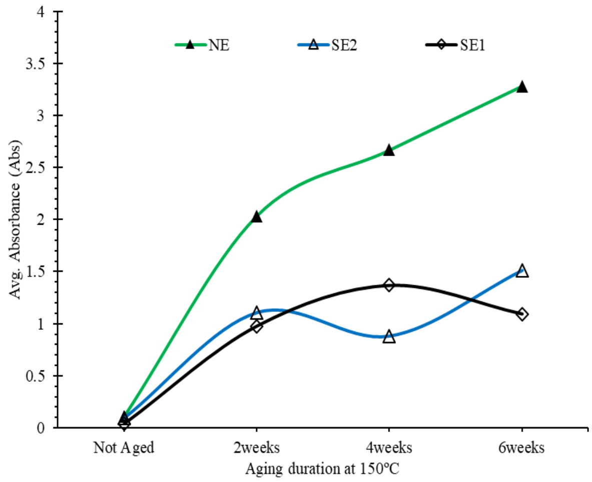
(b) Spectral curves after 2 weeks of aging



(c) Spectral curves after 4 weeks of aging



(d) Spectral curves after 6 weeks of aging



(e) Variation in absorbance of the oils

Figure 2. UV/Vis spectral curves of the oils with aging time

The results presented in Figure 2 (a-d) are an average of three scans, of measured absorbance as a function of wavelengths. Figure 2(e) is the illustration of the average absorbance (average of absorbance values at all wavelengths from 360-600). It is to be noted that natural esters indicate a high absorbance, which might not necessarily be due to its degradation, but more probably to its high absorbance property. SE1 and SE2 show similarities in their degradation over time, although with some experimental fluctuations in the results for 4 and 6 weeks.

Turbidity

Turbidity indicates the ability of the liquid to transmit light through it. It is also a measure of the degree to which the transparency of a liquid is affected by suspended and dissolved particles. Turbidity of the oils was measured as per ASTM D6181 after 2 weeks, 4 weeks, and 6 weeks of thermal aging. It is to be mentioned that the ASTM D6181 test method is applicable for mineral insulating oils only. Turbidity of mineral oil is not presented to avoid a direct comparison of ester fluids to mineral oils. With an increase in the age of oil/paper insulation and the consequent increase in oxidation products, and several other decay contents, the colour of the oil changes and its turbidity is expected to increase [11]. The variation in turbidity with aging for different oils is illustrated in Figure 3. Turbidity of the oils before thermal stresses (non-aged oils) was also measured to establish a base line.

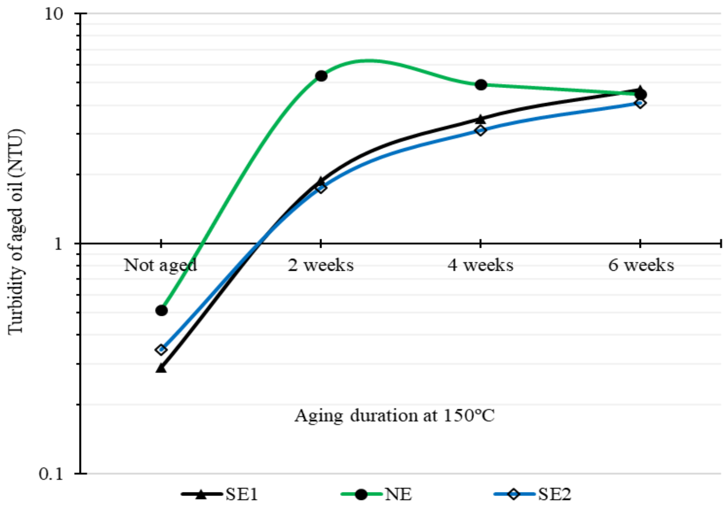
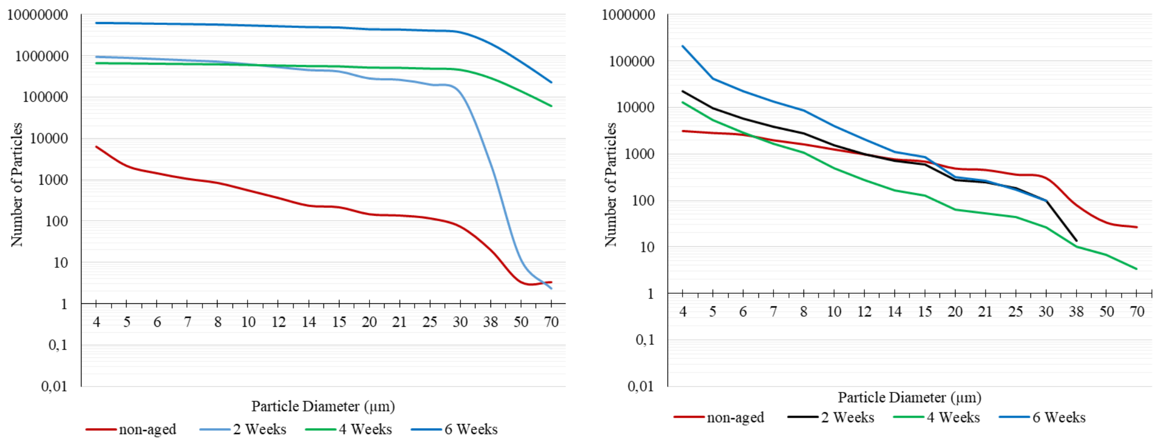


Figure 3. Change in turbidity of various oils with aging time

Turbidity of SE2 and SE1 indicated lowest values at all the aging factors. A good agreement was observed between the increase in absorbance (see Figure 2) and turbidity under continuous aging conditions.

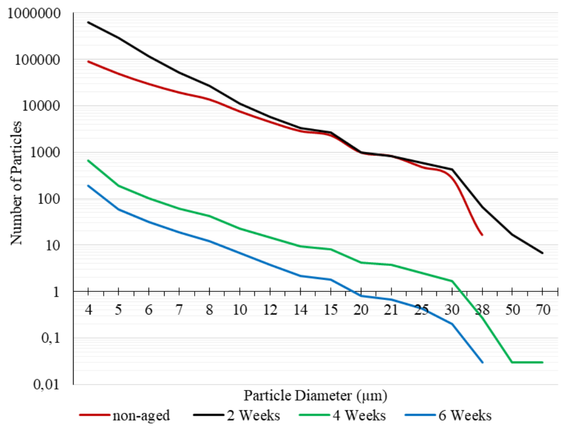
Particle Count

To further evaluate the deterioration of insulation oils, particle counter measurements were taken at different aging conditions. The number of particles in oil are presented as a function of the diameter of the decay particles. Variation of the decay particles of the oils considered in this study are presented in Figure 4. It is to be mentioned that the particle counter measurements are measured as per ASTM D6786 in cumulative counting mode. This cumulative particle count mode is the reason for the decreasing nature of the curves in all the measurements with increase in particle diameter.

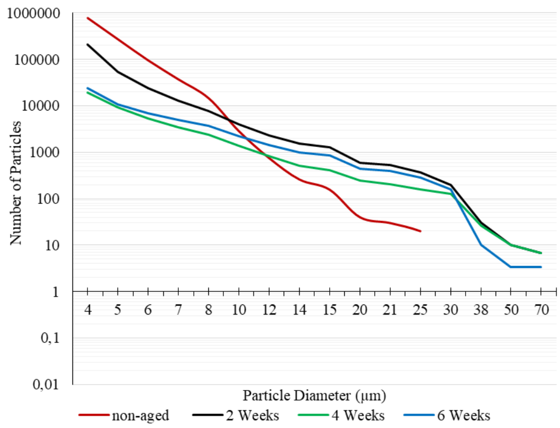


(a) Mineral oil

(b) Synthetic ester 1 (SE1)



(c) Synthetic ester 2 (SE2)



(d) Natural ester

Figure 4. Changes in particle count with aging time

As the number of higher-diameter particles in ester-based dielectric fluids is low, this count shifts the curve close to the x-axis. Note that the number of higher-diameter particles is greater in mineral oils than ester fluids. There are no noticeable changes in particle count for SE1 and there is a slight increase in aging time in the size of particles for NE. In addition, a decrease in the number of higher-diameter particles in SE2 has also been observed for 4 and 6 weeks of aging. The presence of higher-diameter particles is expected to compare unfavourably with smaller-diameter particles. Smaller-diameter particles might include cellulose particles, fibres, gel particles, and carbon particles, whereas higher-diameter particles include the above, as well as micro metal particles [13].

CONCLUSION

In this study, the oxidative degradation of a very low pour point synthetic ester-based fluid was preliminarily investigated. UV spectral studies, turbidity, particle count, and viscosity (from -35°C to 20°C) were reported. Changes in turbidity and absorbance were similar in both synthetic esters.
From this study, it can be inferred that the new low pour point synthetic ester fluid (SE2) is comparable to the other synthetic ester (SE1) in terms of the oxidative degradation tests and experimental conditions. SE2 showed better fluidity at low temperatures than SE1 and NE, which could contribute to its potential application in transformers serving cold climatic regions. Nevertheless, further study is required to understand its aging behaviour and overall performance.

ACKNOWLEDGEMENTS

This work was co-sponsored by the Natural Sciences and Engineering Research Council of Canada (NSERC), Hydro Québec (Grant No. RDCPJ513264-17) and InnovÉÉ (R11-1707). Thanks are also extended to K.M.L. Yapi from Université du Québec à Chicoutimi, Canada, for her help and timely support extended during aging and characterization of the samples.

BIBLIOGRAPHY

[1] I. Fofana, "50 years in the development of insulating liquids," IEEE Electr. Insul. Mag., Vol. 29, No. 5, pp. 13–25, 2013.

[2] I. Fernandez, A. Ortiz, F. Delgado, C. Renedo, S. Perez, "Comparative evaluation of alternative fluids for power transformers," Electr. Pow. Sys. Res., Elsevier, Vol. 98, pp. 58–69, 2013.

[3] U. Mohan Rao, Y. R. Sood, R. K. Jarial, "Ester Dielectrics: Current perspectives and future challenges," Taylor & Francis, IETE Tech. Rev., Vol. 34, No. 4, pp. 448-459, 2017.

[4] L. Raeisian, H. Niazmand, E. E. Bajestan, P. Werle, "Feasibility Study of Waste Vegetable Oil as an Alternative Cooling Medium in Transformer," Applied Thermal Engineering, Vol. 151, pp. 308–317, 2019.

[5] D. Martin, T. Saha, L. McPherson, "Condition Monitoring of Vegetable Oil Insulation in In-Service Power Transformers: Some Data Spanning 10 Years," IEEE Electr. Insul. Mag., Vol. 33, No. 2, pp. 44–51, 2017.

[6] A. A. Abdelmalik, "The feasibility of using a vegetable oil-based fluid as electrical insulating oil", Ph.D. dissertation, Dept. of Eng., University of Leicester, 2012.

[7] U. Mohan Rao, Y. R. Sood, R. K. Jarial, "Performance analysis of alternate liquid dielectrics for power transformers," IEEE Trans. on Dielectr. Electr. Insul., Vol. 23, No. 4, pp. 2475–2484, 2016.

[8] O. Arroyo, I. Fofana, J. Jalbert, S. Gagnon, E. Rodriguez-Celis, S. Duchesne, M. Ryadi, "Aging Characterization of Electrical Insulation Papers Impregnated with Synthetic Ester and Mineral Oil: Correlations Between Mechanical Properties, Depolymerization and Some Chemical Markers," IEEE Trans. on Dielectr. Electr. Insul., Vol. 25, No. 1, pp. 217–227, 2018.

[9] B. Garcia, T. Garcia, V. Primo, J. C. Burgos, D. Urquiza "Studying the Loss of Life of Natural-Ester-Filled Transformer Insulation: Impact of Moisture on the Aging Rate of Paper," IEEE Electr. Insul. Mag., Vol. 33, No. 1, pp.15–23, 2017.

[10] S. P. Moore, W. Wangard, K. J. Rapp, D. L. Woods, R. M. D. Vecchio, "Cold start of a 240-MVA generator step-up transformer filled with natural ester fluid," IEEE Trans on Pow. Deli., Vol. 30, No. 1, pp. 256–263, 2015.

[11] Y Hadjadj, I. Fofana, J. Sabau, E. Briosso, "Assessing insulating oil degradation by means of turbidity and UV/VIS spectrophotometry measurements," IEEE Trans on Dielect. and Electr. Insu., Vol. 22, No. 5, pp. 2653–2660, 2015.

[12] U. Mohan Rao, Y. R. Sood, R. K. Jarial, "Oxidation stability enhancement of a blend of mineral and synthetic ester oils", IEEE Electr. Insul. Mag., Vol. 32, No. 2, pp. 43–47, 2016.

[13] S. Degeratu, P. Rotaru, S. Rizescu, S. Danoiu, N. G. Bizdoaca, L. I. Alboteanu, H. O. Manolea, "Condition monitoring of transformer oil using thermal analysis and other techniques," Journal of Thermal Analysis and Calorimetry, Vol. 119, No. 3, pp. 1679–1692, 2015.