Compatibility of ester oil with transformer components and comparison with mineral oil

Ankita Garg, Apurti Jain

Department of Electrical and Instrumentation Engineering

Thapar Institute of Engineering and Technology

Patiala, Punjab, India

ankita19garg95@gmail.com

Jeyabalan Velandy

Transformer technology in R & D

CG Power and Industrial Solution Limited

Kanjur Marg (E), Mumbai, Maharastra,India

jeyabalan.velandy@cgglobal.com, jeyabalan27@gmail.com

C.S. Narasimhan, Jitendra D. Patil, Sohan S. Beldar

R & D

Savita Oil Technologies Limited

Navi Mumbai, Mumbai, India

csnarasimhan@savita.com

jdpatil@savita.com

ssbeldar@savita.com

***Abstract*— Transformer insulation is a composite system made of insulating liquid and impregnable solid insulation. Generally, the mineral oil is used for insulating medium and cooling of transformers. Recently, the ester oil is becoming increasingly popular as a potential alternative to mineral oil for transformer applications. Insulating oil and impregnated solid insulation in service is subjected to heat, oxygen and electrical discharge, which may lead to its degradation. Hence, Compatibility between the materials which are used in the transformer manufacturing such as varnishes, insulation paper, paint, gasket, core etc., and ester oil must be taken into account for selection of suitable materials. It is also necessary for setting up the process guidelines for ester oil transformers in the real operation to maintain its reliable operation. In this study, material compatibility tests had been performed as per ASTM D3455-11 in order to evaluate the performance of materials with the ester oils of different types (natural ester and synthetic ester) in comparison to conventionally used mineral oil. The studies are of great interest for transformer manufacturers to decide a best compatible material with an insulating oil for a suitable transformer application.**

Index Terms - **Transformer, Ester oil, Bio-degradable, Compatibility test, Breakdown Voltage, Interfacial tension, Dissipation Factor.**

I. INTRODUCTION

Transformers have been in operation over a century, yet they are still a matter of interest to research enthusiasts. The quality and reliability of transformers weigh heavily on controlled manufacturing processes, good design practices and the use of proper insulating materials [1-3]. The verification and testing of insulation design are important for optimizing the material cost as it deeply affects the reliable performance of the transformer. Conventionally, mineral oil is used in the transformers but now-a-days ester oil have gained importance in the transformer insulating applications due to their higher fire point, better thermal performance and biodegradability [1, 4-7]. Hence, considering their environmental friendliness and the fire safety benefits, the transformer utilities are now-a-days prefer to ester oils for transformer applications replacing the conventional petroleum origin based mineral oil [8-10].

In this paper, effect of liquid insulation with the various transformer construction materials has been discussed and its results can be used as the basic guidelines for transformer manufacturers using ester oil in the transformers. The main objective is to study the material compatibility to predict the behavior of various transformer construction materials like kraft paper, current transformer (CT) cloth cover, nitrile damping washer, fiber glass rod, insulating tape with the insulating oil.

This study is expected to support in selecting the right choice of materials for construction of transformer besides helping to reject non-compatible materials. Therefore, Section II of this paper gives a brief introduction about transformer insulating oils, benefits of alternative insulating oils in the power industries and the need for material compatibility for process guidelines for a transformer manufacture and operation. Section III provides the list of materials and insulating oil used for testing. Section IV deals with methodology employed for checking material compatibility. The section V discusses the results of compatibility and finally Section VI provides the conclusion of the study followed by the list of references. The compatibility results are of general applicability and may be used for any electrical insulation applications to avoid failures.

II. MATERIALS AND INSULATING OILS

In this paper, three insulating oils (mineral oil, natural ester and synthetic ester) having different physical, chemical and electrical properties have been used. The properties of various oils used for transformer applications are described in Table I. Mineral oil having petroleum-based origin contains a mixture of paraffinic, naphthenic and aromatic compounds. Naphthenic based mineral oil has more polar features than paraffinic oil due to presence of aromatic contents. Mineral oils may also contain inhibitors to improve the oxidation stability of oil. Ester oils can be classified as natural ester oil (originated naturally from vegetable seeds) and synthetic ester oil (synthetically processed with acids). A natural ester oil has unsaturated fatty acids which accounts for their lower oxidation stability than synthetic ester oil for transformer applications. In addition, natural ester oil has more polar contents than mineral oils due to the presence of ester linkages.

Considering the mineral oil as the reference for the experimental analysis, natural ester oil and synthetic ester oil have been compared for the transformer applications in terms of material compatibility of solid insulation with ester oil. The list of transformer construction materials along with the respective application in transformers has been given in Table II. The compatibility results are of general applicability and may be used for all any electrical insulation applications to avoid failures.

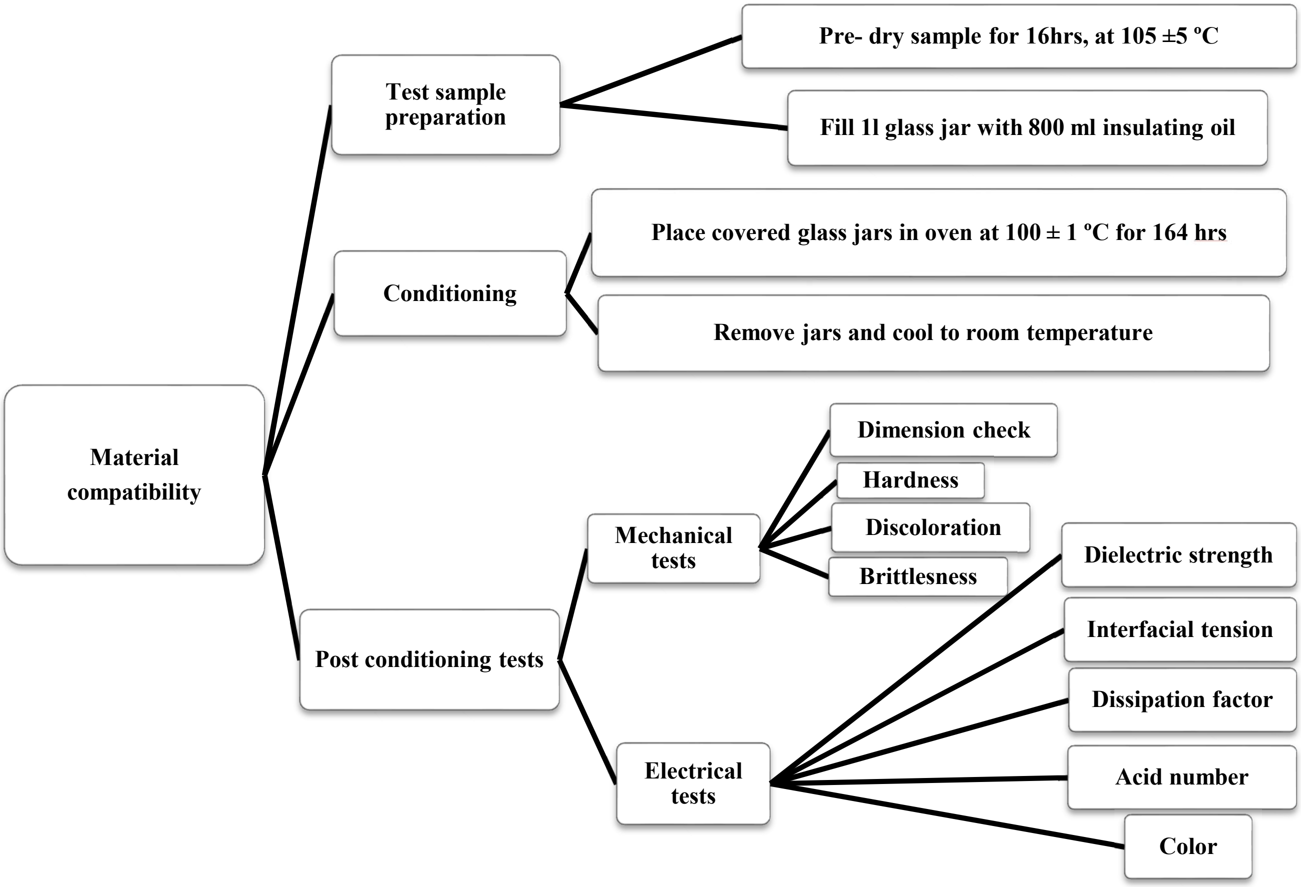

Fig.1. Flowchart of material compatibility test procedure [11]

TABLE I. PROPERTIES OF TRANSFORMER INSULATING OILS

Property	Mineral oil	Natural ester oil	Synthetic ester oil
Relative permittivity	2.2	3.3	3.2
Moisture saturation in ppm at 20 ºC	55	1100	2200
Acid Number in mg KOH/g	0.01	0.04	0.03
Breakdown voltage in kV at 2.5mm gap	>70	>75	>75
Dissipation factor at 90 ºC	< 0.001	0.02	0.03
Viscosity at 40°C mm^2/sec	9.1	35	28
Interfacial tension in mN/m	40	24	25

TABLE II. FUNCTIONS OF TRANSFORMER CONSTRUCTION MATERIALS

Material	Function
CT cloth cover	Used in CTs for bushings
Nitrile damping washer	Gaskets to avoid oil leakage
Fiber glass rod	Used for coil support
Kraft paper	Used as solid insulation on winding conductors
Insulating Tape	Provide mechanical support to the windings

III. METHODOLOGY

Detailed method as described in ASTM D3455 has been followed for compatibility testing. Briefly, the procedure involves the preparation of test specimen for testing and then keeping the sample in contact with the oil for 164 hours and then performing tests on the sample specimen and oil. Corresponding blank experiments are carried out wherein the oil is aged without material. “Fig 1” shows the flow chart for the procedure followed in material compatibility test. The ratio of material in oil has been taken as per transformer applications.

A. *Preparation and conditioning of test specimen*

The following steps were followed for preparation of test specimen and its conditioning [11]:

1. Preconditioning of test specimens at 105 ± 5^0C and 10 mbar vacuum for 16 hours to remove the surface moisture and preserved in vacuum desiccators.
2. Drying Glassware at 120 ± 1^0C for 5 hours and preserving it in vacuum desiccators.
3. Nitrogen through oil is being bubble dried for 10 minutes.
4. The glass jars are then covered and placed in oven at 100 ± 1^0C for 164 hours.
5. After taking the glass jars out from the oven, the tests on insulating oil and test specimen are being performed.

B. Post conditioning tests

After the preparation of test sample and its conditioning, sample is taken out from the glass jar which is filled with oil, using a pair of tongs. Then the tests are performed on the insulating oil and on the transformer construction material which is used in a particular compatibility experiment.

Electrical tests performed on oils are:

1. Dielectric breakdown voltage (BDV)
2. Dissipation factor (tanδ)
3. Interfacial tension (IFT)
4. Acid number (NN)
5. Color

Mechanical tests conducted are the following:

1. Swelling or dimensional Change
2. Hardness check
3. Discoloration
4. Brittleness

Experiments are carried out in triplicate to declare a material to be compatible or incompatible. Blank experiments are carried out on all the types of oil wherein the oil is aged for 164 hours without any material. Ideally, for a material to be compatible, the oil parameters aged in material should not be too distinct from the blank values. However, the oil to material ratio and its exposure to oil in actual transformer should be taken into account and allowances may be made accordingly to oil parameters. Judgments on specific material compatibility will be based on the considerations explained as above.

IV. Experimental Results and Discussions

A. Compatibility studies between Insulating oil and transformer construction materials

Electrical and mechanical tests are performed to evaluate the compatibility status of transformer construction materials with different insulating oils. The basic guidelines on which the compatibility decision is taken to check the dimensional changes in the material before and after its ageing with insulating oil followed by analyzing the corresponding changes in oil properties. After analyzing all the properties, if changes in two or more properties exceed the limits as mentioned in Table III, then the material is declared as incompatible. Detailed interpretation of experimental data for kraft paper and nitrile damping washer has been shown in Table IV. It is on the basis of percentage changed in the oil and material properties before and after conditioning, decides the compatibility status of a particular material.

TABLE III: Compatibility limits for oil properties [11]

Oil properties	Permissible limits
Dielectric strength	28 kV min
Dissipation Factor	1.1% max change
Interfacial Tension	38mN/m min
Acid Number	0.03 mg KOH max change
Color	0.5 max change

Other materials such as CT cloth cover, fiber glass rod and Insulating tape give unsatisfactory results in case of ester oil as compared to mineral oil. However, the weight to volume ratio of these materials to oil in the transformer is very small. Therefore, their effect can be neglected in transformer applications but it should be taken into consideration for the applications whereas ratio of these materials in contact with oil is more. For example, in case of transformer applications, quantity of CT cloth cover usage is very small but in case of CTs in which the cloth quantity used is larger. Hence, this material should be replaced with other material that is compatible with the ester oil in order to avoid failure oil filled current transformer failure at site [2-7, 11-17].

B. Compatibility limits for oil properties

The considerations applied for deciding on compatibility is presented here by considering nitrile damping rubber and kraft paper as an example. For kraft paper, the dimensional changes are in the range of 0.2-1% which is almost negligible in case of transformer applications. But in case of nitrile damping washer, the percentage changes varies in the range of 0.7-18% which cannot be neglected. Further, it can be observed that for mineral oil these changes are negligible (0.7-1%) as compared with ester oils in contact with nitrile damping washer.

After checking the material properties, the oil properties in contact with both the materials are analyzed. It has been observed that there is significant increase in dissipation factor, acid number and decrease in dielectric breakdown voltage, interfacial tension for nitrile damping washer whereas these changes are negligible for kraft paper. Considering the changes in material and insulating oil properties, the compatibility status of a material is determined. Both kraft paper and nitrile rubber are compatible with mineral oils. The results also confirm that kraft paper is compatible with ester oils. However, the compatibility of nitrile rubber with ester oils needs further investigation.

The quality of nitrile rubber gasket is critically dependent on the composition of the polymer. Normally the acrylonitrile (ACN) content varies from 15% to 50% in the polymer. Higher the ACN content, the higher will be resistance to oil. The mechanical properties like compression set and hardness improve and make it suitable as a gasket for systems when oil is in contact. The manufacturer needs to carefully in optimizing the composition to suit each application necessity. Hence, the quality of the gasket can vary significantly from each manufacturer. Therefore, the gasket from every manufacturer has to be evaluated carefully to determine suitability and compatibility with ester oil for transformer applications. If the manufacturing and process quality is not suited for ester oil, then resistance to oil will decrease causing swelling and abnormal dimensional changes.

From the unusual abnormal dimensional changes (18% changes in width) as observed in the Table III, indicates that the manufacturer has supplied a bad quality of gasket. Therefore, the chemical composition of the materials used in the gasket should be properly observed to get accurate compatibility results for ester oil transformer applications and hence to avoid transformer failures at site.

TABLE IV. ANALYSIS OF RESULTS OBTAINED FROM COMPATIBILITY TESTING

Tests on oil and material		Mineral oil			Natural ester oil			Synthetic Ester Oil		
		Blank oil	Kraft paper + oil	Nitrile Damping washer + oil	Blank oil	Kraft paper + oil	Nitrile Damping washer + oil	Blank oil	Kraft paper + oil	Nitrile damping washer + oil
Dielectric strength (kV)		51	45	34	100	92	81	95	90	80
Dissipation factor (%)		0.019	0.02	0.02	0.38	0.4	0.84	0.69	0.72	0.77
Interfacial tension (mN/m)		43	40	38	24	23	22	29	26	25
Acid number (mg KOH/gm)		0	0	0	0.06	0.06	0.06	0.029	0.042	0.088
Color		0.5	0.5	0.5	0.2	0.2	0.2	0.5	0.5	0.5
Dimensional changes	% Change in length	-	0.7	0.8	-	0.5	6	-	0.3	7
	% Change in width	-	0.6	0.7	-	0.4	4	-	0.2	6
	% change in thickness	-	0.6	3	-	0.5	18	-	0.4	13
% change in weight		-	1	1	-	0.4	35	-	0.4	25
Compatibility status			Yes	Yes		Yes	**No**		Yes	**No**

A detailed description along with the graphical representation of the various tests is elaborated to predict the behavior of an incompatible material with discussed below taking Nitrile damping washer as an example. Further, the increment percentage in the oil parameter for all the three insulating oils is also compared to decide the best suitable oil in a transformer.

1) *Dielectric breakdown strength*: The breakdown strength of insulating oil is an indicative of the voltage withstand capability of the insulating oil under high voltage application [12]. Insulating oil in contact with an incompatible material may contain certain dissolved impurities which can affect dielectric strength of the oil.

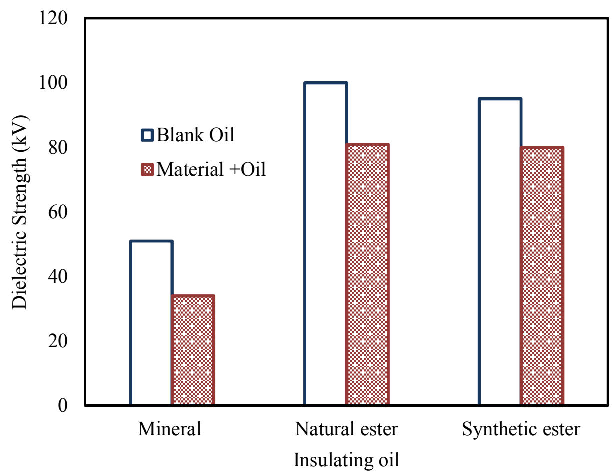

Fig. 2. Change in dielectric strength of insulating oil

From "Fig 2", following conclusions for nitrile damping washer can be drawn:

- Dielectric breakdown strength of mineral oil is less than that of the ester oil
- For mineral oil, there is around 10% decrease in breakdown voltage
- The percentage changes in breakdown strength in case of natural and synthetic ester oil are 19% and 15% respectively.

Therefore, the change in breakdown strength of nitrile damping washer are more in case of ester oil as compared to mineral oil.

2) *Dissipation factor*: Pure ester oils have higher dissipation factor compared to pure mineral oil which is due to the inherent chemical nature of the ester linkage. Therefore, the increase of percentage in the oil parameter after ageing with material is compared with the value of the same oil parameter aged without material is taken for deciding the compatibility of the material with insulating oil instead of the absolute increase in values [13].

Following inferences are drawn from "Fig 3":

- Dissipation factor of blank mineral oil is less than that of both natural as well as synthetic ester oils.
- There are significant variations in dissipation factor of natural ester (approx. 120%) whereas for synthetic ester is 11%.
- For mineral oil, the change is 0.5% which is acceptable as per ASTM standards.

Therefore, dissipation factor is an important parameter to determine the compatibility status of a material.

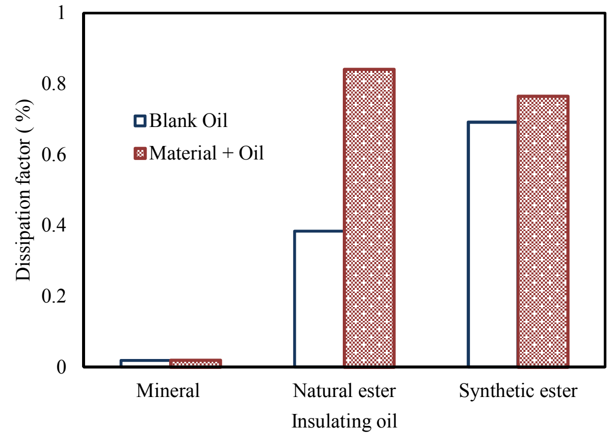

Fig. 3. Change in dissipation factor of insulating oil

3) *Interfacial tension*: IFT measures the presence of polar impurities in an oil. As mineral oil is non-polar in nature, even small polar quantity in mineral oil has significant effect on the IFT value, whereas esters themselves are polar in nature and hence IFT is not much sensitive to polar impurities as compared to mineral oil [14].

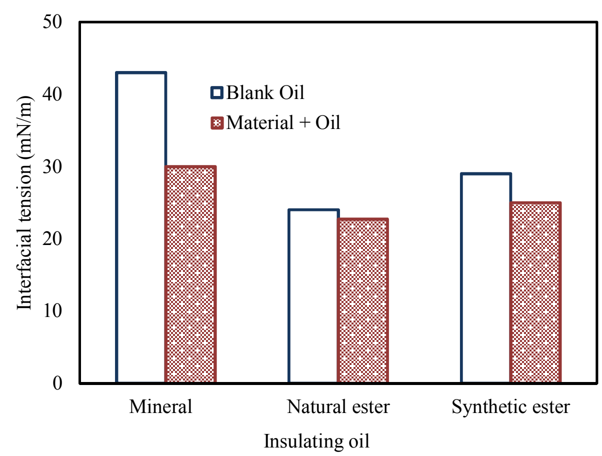

Fig. 4. Change in interfacial tension of insulating oil

From "Fig 4", following conclusions are observed:

- For mineral oil, there is around 11% decrease in IFT.
- The percentage changes in IFT in case of natural and synthetic ester oil are 8% and 14% respectively.

Hence, IFT is more sensitive to mineral oil impurities as compared with ester oil and cannot be used as the only parameter to decide the compatibility for ester oils.

4) Acid number: Neutralization number also termed as acid number and it measures the amount of fatty acids present in the oil sample [15]. These acids in the oil mix with solid insulation and cause its degradation.

From "Fig 5", following inferences are taken:

- The base value of ester oil in itself are higher than that of mineral oil
- Almost the negligible changes in acid number for both mineral and natural ester oil
- Acid number is almost doubled for synthetic ester oil.

Therefore, acid value is very sensitive to ageing with materials in case of synthetic ester.

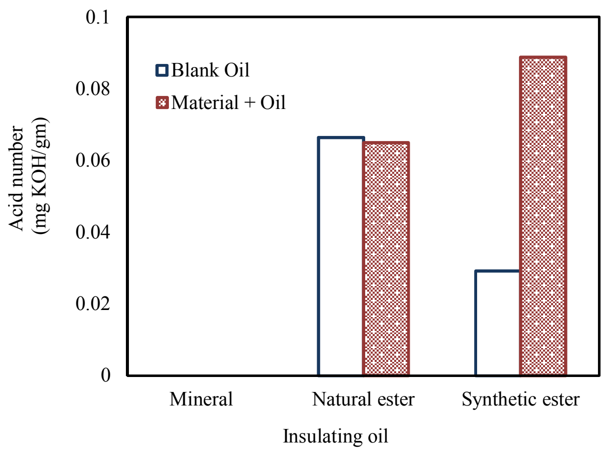

Fig. 5. Change in acid number of insulating oil

5) Color: The test involves the comparison of oil sample color with color code that shows color change from light yellow to dark brown. This test alone is not sufficient to decide the compatibility of a particular material with the insulating oil. It is found that oil sample of the material which is not compatible shows no color change before and after the test whereas oil sample of a compatible material showed a change in color [16]. Therefore, from the above results obtained from various tests for determining the compatibility studies, it can be stated that the presence of an incompatible material with the insulating oil have detrimental effects on the performance of transformer. Hence, care must be taken while using new materials or new insulating oil in the transformer in order to avoid the transformer failures at site.

V. CONCLUSIONS

Material compatibility is considered to be an important guiding factor for material selection and setting up the process guidelines for transformer. In the paper, material compatibility tests had been performed to check the compatibility of transformer construction materials with ester oil and then the results were compared with mineral oil results. Incompatibility may lead to the increase in dissipation factor, resulting in reduction of the dielectric strength of the oil and increase in dielectric losses resulting in the increase of fault gases that in the long run may prove destructive for the transformer applications.

The highly abnormal values indicating the incompatibility of nitrile rubber has been attributed to bad quality of the material supplied. The other materials like fiber glass tape, insulating tape, CT cloth cover and damping washer can be used with ester oil in transformer applications. Its ratio of their weight to volume of oil used in transformer is very low and their effect can be neglected but their use must be avoided in those applications where the weight to volume ratio is more. Nitrile rubber is produced in many grades, some of which may contain additives or binders. Hence, chemical composition of nitrile rubber plays an important role in transformer and must be properly checked as per the requirements in applications to avoid misleading results in the compatibility studies.

REFERENCES

[1] A. Abdel malik, “Analysis of thermally aged insulation paper in a natural ester-based dielectric fluid,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 22, No. 5, pp. 2408-2414, 2015.

[2] Y.H. Qian, W. Su, Y.B. Huang and Z.S. Zhong, “Experimental study of the compatibility of insulating oil in transformers,” Materials Research Innovations, Vol. 19, pp. S8-680-S8-684, 2015.

[3] L. R. Lewand, “Material compatibility of gasket materials in insulating liquid,” 80th International Conference of Doble Clients, pp.1-16, 2013.

[4] N. Bernard and B. Cucek, “Compatibility of mineral insulating oil with transformer construction materials,” IEEE 19th International Conference on Dielectric Liquids (ICDL), 2017.

[5] K. Bandara, C. Ekanayake, T. Saha and H. Ma, “Performance of natural ester as a transformer oil in moisture-rich environments,” Energies, vol. 9, no. 4, 1 4 2016.

[6] H. M. Wilhelm, V. Franch, L. Tulio and A. F. Franch, “Compatibility of transformer construction materials with natural ester-based insulating fluids,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 22, No. 5, pp. 2703-2708, 2015.

[7] Q. Huang, B. Wang, J. Li, L. Yang and R. Liao, “The compatibility tests between vegetable insulating oil and mineral insulating oil,” International Conference on High Voltage Engineering and Application (ICHVE) 2014.

[8] L. Yang, R. Liao, C. Sun and H. Sun, “Influence of natural ester on thermal aging characteristics of oil-paper in power transformers,” European Transactions on Electrical Power, Vol. 20, No. 8, pp. 1223-1236, 2010.

[9] M. S. Shim, “Comparative evaluation of aging of insulating material in natural ester and mineral oil,” International Conference on High Voltage Engineering and Application (ICHVE), 2010.

[10] A. Abdelmalik, J. C. Fothergill and S. J. Dodd, “Aging of Kraft paper insulation in natural ester dielectric fluid,” in Proceedings of IEEE International Conference on Solid Dielectrics, ICSD, 2013.

[11] ASTM D3455, Standard test methods for compatibility of construction material with electrical insulating oil of petroleum origin, ASTM, 2011.

[12] ASTM D877, Standard test method for dielectric breakdown voltage of insulating liquids using disk electrodes, ASTM 2011.

[13] ASTM D924, Standard test method for dissipation factor (or power factor) and relative permittivity (dielectric constant) of electrical insulating liquids, ASTM, 2009.

[14] ASTM 1533, Standard test method for interfacial tension of oil for moisture, ASTM 2011.

[15] ASTM D974, Standard test method for acid and base number by color- indicator titration, ASTM, 2004.

[16] ASTM D1500, Standard test method for ASTM Color of petroleum products (ASTM color Scale), ASTM, 2003.

[17] ASTM D3612, Standard test method for analysis of gases dissolved in electrical insulating oil by gas chromatography, ASTM, 2009.