Electrical and Electronic Engineering 2012, 2(3): 141-146
DOI: 10.5923/j.eee.20120203.06

Aging of Paper Insulation in Natural Ester & Mineral Oil

Yunus Biçen[1,*], Yusuf Çilliyüz[2], Faruk Aras[2], Guzide Aydugan[3]

[1]Industrial Electronics Dept. Duzce Univ. TR-81010 Uzunmustafa Duzce, Turkey
[2]Electrical Edu. Dept. Kocaeli Univ. TR-41380 Umuttepe Izmit, Turkey
[3]Schneider-Electric Turkey, TR-41410 Gebze Kocaeli, Turkey

Abstract This paper presents an assessment on aging model of IEEE and IEC standards using thermal model of oil-immersed power transformer for natural ester and mineral oil. For this purpose, a model created for the behaviour of transient thermal performance with aging of natural ester and mineral oils. Thermal model of the transformer is based on thermal-electrical analogy that is calculated separately for natural and mineral oils covering top-oil and hot-spot temperatures. The hot-spot temperature values of each ester/oil are used to calculate aging parameters which include the aging acceleration factor, time dependent relative aging rate and insulation life loss variations. In this study, mineral oil and natural ester are kept under temperatures which are 100°C and 140°C in different periods. Natural ester's characteristics are higher than mineral oil's, except its breakdown voltage. In addition, natural ester absorbs more water than mineral oil so it is understood that deformation of the insulating paper in natural ester is lower. Natural ester has important benefits to decelerate aging of insulation. There is a model which is proposed for natural ester oil–immersed transformers and there should be used an aging factor as *R* to predict remaining life.

Keywords Aging, Paper Insulation, Thermal Model, Natural Ester, Mineral Oil

1. Introduction

Today, clean energy is emerging as a new trend in electric power systems. Therefore, green oils have been preferred as liquid insulator in power transformers especially since 2000. Green oils have three most important features, have slow down the impact of the aging process; provide a safe work performance and are biodegradable as close to 100%. Green oils named as the natural esters can be mixed with mineral oils and their utilization rates are increasing every day due to non-toxic and eco-friendly features.

Thermal aging of insulation materials in mineral oil–immersed transformers have been formulated in ANSI/IEEE–C57.91 and IEC–354.91 standards[1, 2]. However, these formulas should be revised again for natural ester due to slow down the aging process. There are some differences between IEEE and IEC standards on thermal aging methods for mineral oil-immersed transformers. According to IEEE, normal lifetime of the power transformers equals to 20.55 years, whereas a total life has not been defined by the IEC standards, but it is usually equal to 30 years depending on the aging rate determined by the hot spot temperature[3, 4]. Hot spot temperature of natural ester–immersed transformers is higher than that of mineral oil–immersed transformers.

* Corresponding author:
yunusbicen@duzce.edu.tr (Yunus BİÇEN)
Published online at http://journal.sapub.org/eee

And it is emphasized that the deviation of the hottest temperature between the two is increased with load[5, 6] because when the natural ester is compared to mineral oil, viscosity is higher and thermal conductivity is lower[5, 6] nevertheless, there is amount of soluble water transferred from Kraft paper to the natural ester more than mineral oils. That's the reason why the paper is slow down aging and less deterioration in natural ester. Other positive features of Natural ester are presented in Table 1.

Table 1. Font Specifications for Dominance Vector

Dominance vector of natural esters to mineral oils, related eco-friendly, aging, cost, safety and reliability features		Dominance vector
Environmental safety	Viscosity*	
Eco-friendly, be recyclable	Thermal conductivity*	
Fire safety	Hot-spot temperature rise	
Transformer material compatibility		
Insulation paper aging rates		
Acidity stability*		
Dissolution of water in oil*		
Mixable with mineral oil		
Dielectric strength		

** These things directly or indirectly affect the hot spot temperature*

In literature, also there are more studies about natural ester and mineral oil. Moisture effects on the electric breakdown strength of transformers boards under voltage in oil are examined[7, 8]. Natural ester has higher absolute humidity and acidity during the long ageing period[9]. Transformer paper in vegetable oil had larger activation energy. Due to the larger interaction force between water and natural ester molecules, water molecule was easily bonded with natural ester, weakening the hydrolysis process of cellulose. Cellulose is chemically modified by natural ester during thermal aging process[10]. Vegetable oil is an alternative to mineral oil and over the temperature range of 70°C to 190°C shows that the use of vegetable oil as a very promising option[11]. Transformer paper is decomposed by water, oxygen, oil acid, high temperatures and eventually degrades to the point where it is no longer an effective insulator[12, 13, 14]. Aging of Kraft paper in mineral or natural ester oils produced important amounts of CO and CO_2[12].

This study suggests that determining the difference of aging period between natural ester and mineral oil should be used factor R so it is possible to predict the lifetime of natural ester oil–immersed power transformers easily and nearly correct.

2. Thermal Model and Life Loss Equations

2.1. Top-Oil and Hot-Spot Thermal Models

The top oil thermal model is based on the equivalent thermal circuit theory proposed by G. Swift. The differential equation for the equivalent circuit is[15];

$$\frac{I^2\beta+1}{\beta+1}.\left[\Delta\theta_{oil-R}\right]^{1/n}=\tau_{oil}\frac{d\theta_{oil}}{dt}+\left[\theta_{oil}-\theta_A\right]^{1/n} \quad (1)$$

where,

I_{pu} is the load current per unit.

θ_A is the ambient temperature, ℃.

θo is the top oil temperature, ℃.

β is the ratio of load to no-load losses

τ_{oil} is the top oil time constant, min.

$\Delta\theta_{oil\text{-}R}$ is the rated top oil rise over ambient, K.

n is the exponent defines non-linearity.

As the same mentioned method, the differential equation used to calculate the hot spot temperature is;

$$\frac{I^2\left[1+P_{EC-R(pu)}\right]}{1+P_{EC-R(pu)}}.\left[\Delta\theta_{H-R}\right]^{1/m}=\tau_H\frac{d\theta_H}{dt}+\left[\theta_H-\theta_{oil}\right]^{1/m} \quad (2)$$

Where,

θ_H is the hot spot temperature, ℃.

$P_{EC\text{-}R(pu)}$ are the rated eddy current losses at the hot spot location

$\Delta\theta_{H\text{-}R}$ is the rated hot spot rise over top oil, K.

τ_H is the winding time constant at the hot spot location, min.

2.2. Insulation Life Loss

The IEEE guide recommends that users select their own lifetime estimation. In this guide, 180 000 hours (20.55 years) are used as a normal lifetime[3].

It is assumed that insulation deterioration can be modelled as a per unit quantity for a reference temperature of 110℃, the equation for accelerated aging is[3,4];

$$F_{AA}=e^{\left[\frac{15000}{383}-\frac{15000}{\theta_H+273}\right]}\ pu \quad (3)$$

The IEC guide is applicable mainly for the non-thermally upgraded paper, and the hot-spot temperature is limited to 98℃ at 20℃ ambient temperature. It can be expressed in the following manner[3, 4]:

$$Aging\ rate\,(V)=2^{(\theta_H-98)/6} \quad (4)$$

The loss of life during a small interval dt can be defined as;

$$dL=F_{AA}dt \quad (5)$$

The loss of life over the given load cycle can be calculated by;

$$L=\int F_{AA}dt \quad (6)$$

and the per unit loss of life factor is;

$$L=\frac{\int F_{AA}dt}{\int dt} \quad (7)$$

The insulation loss of life is usually taken to be a good indicator of transformer loss of life.

3. The Proposed Method and Transient Modelling

In this study, two different models are created in Matlab-Simulink for natural ester and mineral oil immersed power transformers which have the same technical specifications (ONAF-250MVA). Parameters of the power transformer were taken in IEEE Loading Guide and specifications are shown in Table 2.

The established model has two stages. In first stage, ambient temperature and load factor are taken as input parameters. The hot-spot temperatures that will be used in loss of life calculation are found out by using these parameters by running the thermal model. However, the hot spot temperature calculation procedures are different for natural ester and mineral oil immersed transformers.

Table 2. 250 MVA Transformer Parameters[2,8]

No Load	78100 W
P_{dc} losses (I^2 R_{dc})	411780 W
Eddy losses	41200 W
Stray losses	31660 W
Rated top oil rise over ambient	38,3℃
Rated hot spot rise over top oil	20,3℃
Ratio of load losses to no load losses	6,20
pu eddy current losses at hot spot location, LV	0,65
pu eddy current losses at hot spot location, HV	0,3
Top oil time constant	170 min
Hot spot time constant	6 min
Exponent n	0,9
Exponent m	0,8

According to the experimental studies in the literature, the difference of temperature rise doesn't exceed 21℃ between natural ester and mineral oil[5, 6 and 16]. At nominal operating conditions, this difference can vary between 5℃ to 10℃[6]. For this reason, a lookup table changing as exponential is intended in the model for natural oil immersed transformer according to the studies in literature.

The second phase of the modelling is the calculation of aging characteristics. Here, different equations are recommended for natural ester (revised) and mineral oil (not revised) to calculate the aging acceleration factor as shown in Table 3. In the literature, it is commonly mentioned that vegetable-based oils prolong life of solid insulation between 5 to 8 times at the same temperature. For this purpose a factor (*R*) should be added to the calculation process of the aging model for natural ester[17].

Table 3. Aging Acceleration Factors[10]

Standards	Mineral Oil (Aging acceleration factors)	Natural Ester (Relatively revised)
ANSI/IEEE C57: 91	$e^{\left[\frac{B}{(383)}-\frac{B}{(\theta_H+273)}\right]}$	$R.e^{\left[\frac{B}{(383)}-\frac{B}{(\theta_H+273)}\right]}$
IEC 354: 91	$2^{\frac{(\theta_H-98)}{6}}$	$R.2^{\frac{(\theta_H-98)}{6}}$
B is the aging rate constant. *θ_H is hot spot temperature.* *R is a ratio of slow insulation aging for natural ester. It can be selected between* *(1/5) and (1/8) according to the characteristics of natural ester.*		

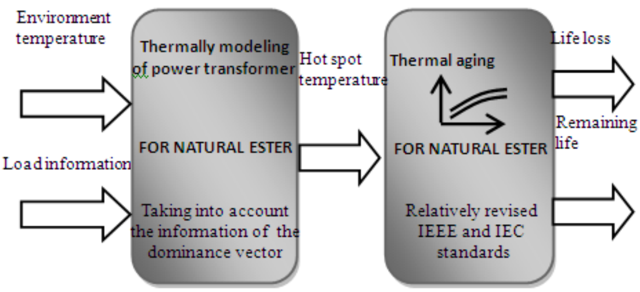


Figure 1. Proposed thermal model and aging calculation stages

In the model, firstly the hot-spot temperatures and secondly aging parameters such as insulation loss-life and remaining life can be calculated taking the ambient temperature and transient characteristics of the load into account for each natural ester/ mineral oil immersed power transformer as shown in Figure 1.

4. Experimental Studies

Samples of mineral oil and natural ester are kept under temperatures of 100℃ and 140℃ for different periods. Test results are given by Table 4, and Table 5 respectively. Images of the held samples are also shown in Figure 2. The results show that characteristics of natural ester are higher than mineral oil, except its breakdown voltage. Additionally, as it can be seen that water content results; natural ester absorbs more water than mineral oil. This means that deformation of the insulating paper in natural ester is lower.

In addition, the results of the gas analysis show that CO_2/CO ratio which defines aging stage of cellulosic insulation material is very different. The ratio is under three for mineral oil, while it is above seven for natural ester.

Equivalent test transformers are operated such condition that corresponds to double rated current in order to evaluate the heating performance of mineral oil and natural ester. Hot spot temperatures are measured by fibre optic sensor. It is observed that the temperature differences of mineral oil and natural ester are between 10℃ and 15℃. The aging characteristic of insulting material is affected from the temperature. The natural ester immersed transformer is more heated than the mineral oil immersed transformer under the same conditions.

Table 4. Mineral Oil and Natural Ester Quality Analysis by IEC 60422 Standard for 100℃

Characteristics	Test Methods	Units	Mineral oil	Natural ester
Dielectric Dissipation Factor (DDF) at 90℃	IEC 60247	Numerical	0,00691	0,064
Dielectric Breakdown Voltage	IEC 60156	kV	76,5	68,3
Water Content	IEC 60814	ppm	3,4	110
Color Number	ISO 2049	-	0,5	1,5
Acidity	IEC 62021-1	mgKOH/g oil	0,1285	0,1776
Interfacial Tension (IFT) at 25℃	ISO 6295	mN/m	32,7	17,7
CO	ASTM 3612	ppm	250	124
CO_2	ASTM 3612	ppm	1	5914

Table 5. Mineral Oil and Natural Ester Quality Analysis by IEC 60422 Standard for 140℃

Characteristics	Test Methods	Units	Mineral oil	Natural ester
Dielectric Dissipation Factor (DDF) at 90℃	IEC 60247	Numerical	0,1461	0,961
Dielectric Breakdown Voltage	IEC 60156	kV	71	49,5
Water Content	IEC 60814	ppm	10,8	106,4
Color Number	ISO 2049	-	8	2,5
Acidity	IEC 62021-1	mgKOH/g oil	0,2428	0,2685
Interfacial Tension (IFT) at 25℃	ISO 6295	mN/m	-	17,5
CO	ASTM 3612	ppm	390	1730
CO_2	ASTM 3612	ppm	1	23809

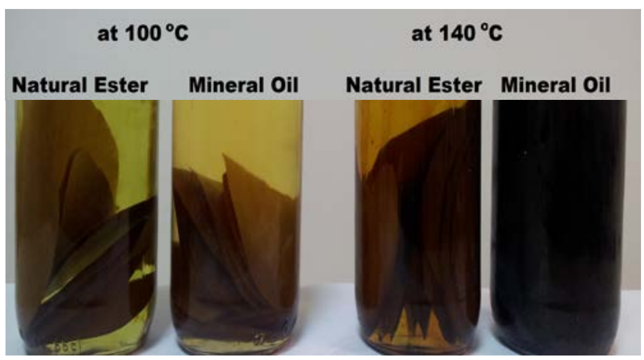


Figure 2. Differences in appearances between natural ester and mineral oil with Kraft papers

According to the some studies on accelerated aging tests in literature, lifetime of the paper aged in natural ester is 5-8 times longer than paper aged in mineral oil at the same temperature values[18]. Actually, the hot spot temperatures taken into account for the aging calculations will be different from each other for natural ester-immersed transformers and mineral oil-immersed transformer. Consequently, as given in section three, the formulas should be revised relatively.

5. Results and Discussions

5.1. Transient Thermal Characteristics

The load step variation for 750 minutes time duration is shown in Figure 3. Calculation of the hot spot temperature and top-oil temperature for mineral oil-immersed power transformer using thermal model are shown in Figure 4. It can be seen that the temperature rise for the certain time periods does not reach to the steady state point.

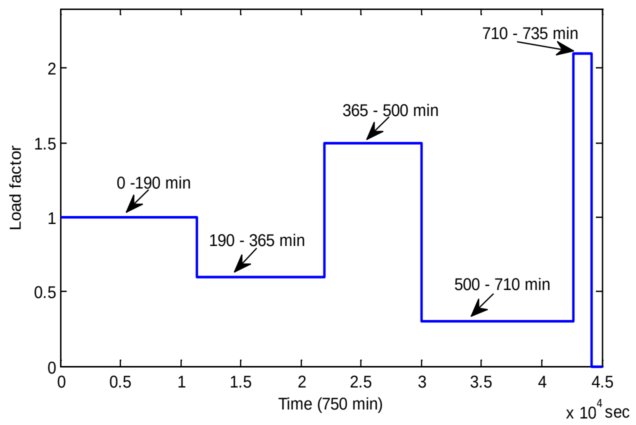


Figure 3. Load step changes (IEC 60076- Part 7)

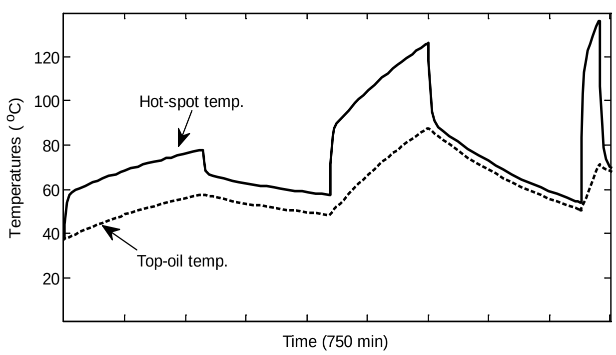


Figure 4. Temperature responses for mineral oil

Under the same time duration, the hot-spot temperature rise calculated for the natural ester and the mineral oil is shown in Figure 5. The difference of the temperature between the natural ester and mineral oil increases as power factor increases. This is because the thermal resistance and thermal capacity of the natural ester are greater than that of the mineral oil.

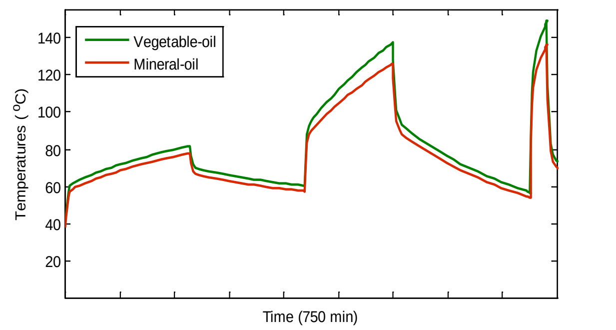


Figure 5. Hot-spot temperature differentiation between natural ester and mineral oil

5.2. Transient Aging Characteristics

In order to determine aging characteristics clearly, the load time duration is increased to 48 hours, and load sample repeats three times in this duration. The following situations are analysed using the model.

- Aging acceleration factor variation
- Time dependent relative aging rate variation
- Life loss variation

Figure 6 (a) and (b) shows the acceleration of aging for natural ester and mineral oil. Although the aging characteristics are the same, the aging acceleration factor of mineral oil is approximately two times higher than that of natural ester. Also, this affects to the relative aging rate. As shown in Figure 7, trend of the relative aging rate instabilities for natural ester and mineral oil decreases as the time increases. The life loss variation of the solid insulation which is misknown as transformer life loss is shown in Figure 8.

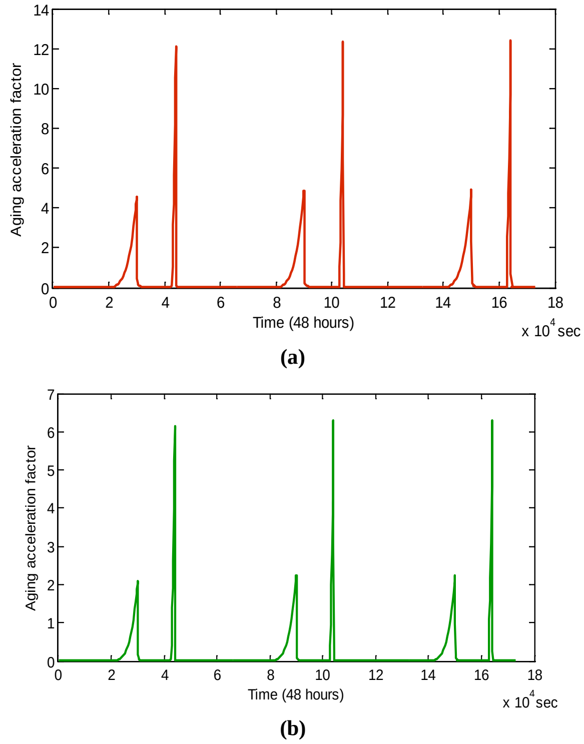
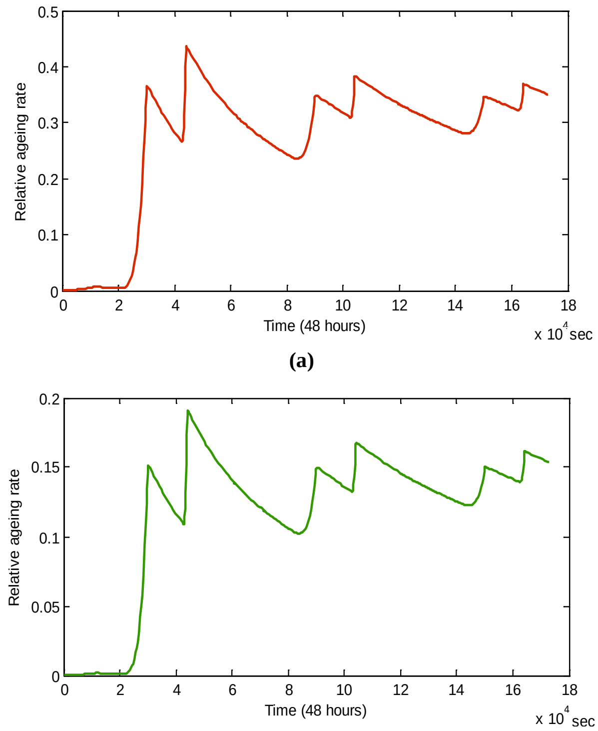


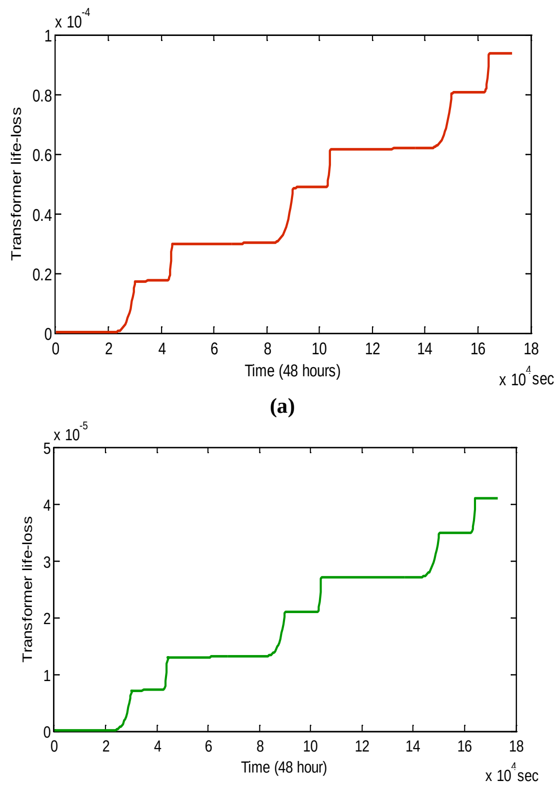
Figure 6. Aging acceleration factor variations, (a) for mineral oil, (b) for natural ester

The life loss of insulation for mineral oil-immersed transformer is two times longer (approximately 2.4 times) than the life loss of insulation for natural ester-immersed transformer under the same conditions.



(b)

Figure 7. Time dependent average relative aging rate variations, (a) for mineral oil, (b) for natural ester



(b)

Figure 8. Life loss variations, (a) for mineral oil, (b) for natural ester

6. Conclusions

The results of this study show that the natural ester has significant benefits in slowing down aging of insulation. Solid insulation life loss variations which is mentioned as 5-8 times slower at the same temperature, experimented by modelling two different 250 MVA power transformers which have the same technical characteristic features for mineral oil and natural ester. The factor R should be added to the proposed model for natural ester and, its temperature rise more than that of mineral oil is also considered in this study. Particularly, natural ester-immersed transformer is very advantageous in the nominal operating conditions. This advantage decreases with increasing load values over the nominal operating condition.

ACKNOWLEDGEMENTS

This work is supported by the Scientific Research Projects Unit of Kocaeli University. Project number: 2010/33.

REFERENCES

[1] IEEE Guide for Loading Mineral-Oil-Immersed Transformers, IEEE C57.91-1995.

[2] Loading Guide For Oil-Immersed Power Transformers, IEC Publication 354, 1991.

[3] K. Najdenkoski, G. Rafajlovski, V. Dimcev, “Thermal Aging of Distribution Transformers According to IEEE and IEC Standards”, Power Engineering Society General Meeting, IEEE, 2007, pp. 1-5

[4] P.K. Sen, P. Sarunpong, “Overloading And Loss-of-Life Assessment Guıdelines of Oil-Cooled Transformers”, Rural Electric Power Conference, 2001 , pp. B4/1 - B4/8

[5] B. Lee, J. Jeong, C. Park, I. Song, “The Characteristics of Winding Temperature for the Natural Ester Filled Transformer up to and Including 500 kVA”, Annual Report Conference on Electrical Insulation Dielectric Phenomena, 26-29 Oct. 2008, pp. 115-117

[6] S.P. Moore, “Some Considerations for New and Retrofill Applications of Natural Ester Dielectric Fluids in Medium and Large Power Transformers”, Transmission and Distribution Conference and Exhibition, IEEE PES, 2006, pp. 25-29,

[7] H.-Z. Ding, Z. D. Wang and P. Jarman, “Ageing and Moisture Effects on the AC Electrical Strength of Transformerboard”, 2007 International Conference on Solid Dielectrics, Winchester, UK, July 8-13, 2007.

[8] H. M. Wilhelm, L. Tulio, R. Jasinski and G. Almeida, “Aging Markers for In-service Natural Ester-based Insulating Fluids”, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 18, No. 3; pp. 714 – 719, June 2011.

[9] Ruijin Liao, Jian Hao, George Chen, Zhiqin Ma and Lijun Yang, “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; pp. 1626 – 1637, October 2011.

[10] Lijun Yang, Ruijin Liao, Sun Caixin and Mengzhao Zhu, "Influence of Vegetable Oil on the Thermal Aging of Transformer Paper and its Mechanism", IEEE Transactions on Dielectric s and Electrical Insulation Vol. 18, No. 3; pp. 692 – 700, June 2011.

[11] Maria Augusta G. Martins, "Vegetable Oils, an Alternative to Mineral Oil for Power Transformers—Experimental Study of Paper Aging in Vegetable Oil Versus Mineral Oil", IEEE Electrical Insulation Magazine – DEIS, Vol. 26, No. 6, pp. 7 – 13, November / December, 2010.

[12] Nick Lelekakis, Wenyu Guo, Daniel Martin, Jaury Wijaya, Dejan Susa, "A Field Study of Aging in Paper-Oil Insulation Systems", IEEE Electrical Insulation Magazine – DEIS, Vol. 28 No. 1, pp. 12 – 19, January / February, 2012.

[13] "Ageing of Cellulose in Mineral-Oil Insulated Transformers," Cigre Brochure 323, 2007.

[14] R. Sanghi, "Chemistry behind the life of a transformer," Resonance, vol. 8, no. 6, pp. 17–23, 2003.

[15] A. Elmoudi, J. Palola, M. Lehtonen, "A Transformer Thermal Model for use in an on-line Monitoring and Diagnostic System", Power Systems Conference and Exposition, IEEE/PES 2006, pp.1092-1096

[16] S.D. Smith, B. L. Beaster, "Design and Test Experience with Natural Ester Fluid for Power Transformers Update", Transmission and Distribution Conference and Exhibition, IEEE/PES, 2006, pp. 35-36.

[17] Y. Bicen, Y. Cilliyuz, F. Aras, G. Aydugan, "An Assessment on Aging Model of IEEE/IEC Standards for Natural and Mineral Oil-Immersed Transformer", IEEE International Conference on Dielectric Liquids 2011, 26-30 June 2011, Trondheim, Norway.

[18] C.P. McShane, K.J. Rapp, J.L. Corkran, G.A. Gauger, J. Luksich, "Aging of Paper Insulation in Natural Ester Dielectric Fluid", Transmission and Distribution Conference and Exposition, IEEE/PES, Oct 28 - Nov. 02 - 2001, vol.2, pp. 675-679.