Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v35i2.15190

Investigations of thermal degradation and spectral response of transformer oil

Karthik Radha[1*] and Sree Renga Raja Thangaswamy[2]

*[1]Liquid Dielectrics Laboratory, National Engineering College, Kovilpatti, Tamilnadu, India-628 503. [2]Departament of Electrical and Electronics Engineering, BIT campus, Anna University, Tiruchirappalli, India. *Author for correspondence. E-mail: hvekarthik@gmail.com*

ABSTRACT. In order to maintain continuous power supply in the electrical system, condition monitoring of the sensitivity equipments in power system is very essential. Among those equipment in which more concentration required is Power transformer. To determine the performance of transformer, it is necessary to have investigations on ageing of transformer oil due to thermal degradation. In this work an effort has been made to analyze various critical parameters like acidity, Breakdown Voltage (BDV), viscosity, volume resistivity, loss tangent, dielectric constant and spectral response for different range of thermal degradation of transformer oil with various compositions of materials like pressboard and Kraft paper. As initiative an exclusive Thermal-UltraViolet (UV) analysis has been carried out to investigate the spectral response of transformer oil. By estimating the condition of oil, the unexpected failure of transformer and power outages can be prevented.

Keywords: transformer, liquid dielectric, loss tangent, resistivity, breakdown voltage.

Investigações sobre a degradação térmica e resposta espectral do óleo de transformador

RESUMO. A fim de manter um suprimento contínuo de energia no sistema elétrico, é essencial que se monitore os equipamentos de sensibilidade no sistema de energia. O transformador está entre os equipamentos que requerem uma maior concentração. Para determinar o desempenho do transformador é necessário que se examine a idade do óleo do transformador devido à degradação térmica. No presente estudo foram analisados vários parâmetros críticos, como a acidez, tensão de ruptura, viscosidade, resistividade de volume, tangente de perda, resistividade, constante dielétrica e resposta espectral para diferentes faixas de degradação térmica do óleo do transformador com variada composição de materiais, como papel cartão prensado e papel Kraft. Além disso, uma exclusiva análise térmica ultravioleta foi realizada para investigar a resposta espectral do óleo do transformador. Através da estimativa das condições do óleo, falhas inesperadas do transformador e de energia podem ser prevenidas.

Palavras-chave: transformador, líquido dielétrico, tangente de perda, resistividade, tensão de ruptura.

Introduction

Major problem faced by the power engineers through out the world is predetermining the life time of transformers. Power transformer life ends before the predicted time because of lack of insulation monitoring. Solid and Liquid insulation system used in transformer are designed to withstand stresses like Power frequency voltage and transient stresses like lightning impulses, switching impulses and short circuits. The deterioration of solid insulation system may be examined by various methodologies like analysis of furan content and Degree of Polymerization. Monitoring of liquid dielectrics is achieved by examining various critical parameters like acidity, BDV, viscosity, volume resistivity, loss tangent and Dielectric constant. Kohtoh et al. presented a characteristics analysis of oil for samples heated to number of days. Han et al. presented various condition monitoring techniques for electrical equipments. Kohtoh et al. discussed about aging effect on electrical characteristics of insulating oil due to degradation. Syed Islam et al. presented a methodology to determine the furan compounds in oil. In this paper as an initiative work, same samples were subjected to different hours of thermal degradation. Various pattern changes in the characteristics of oil due to degradation were studied. An exclusive Thermal –UV analysis were carried out, in which degraded transformer oil were subjected to UV-Visible light and their spectral responses were examined. Based on the bandwidth (nm) and absorption capability of transformer oil, level of degradation can be determined.

Material and methods

Experiments are conducted as per American Society of Testing and Materials (ASTM, 2012 a and b), Indian standards (IS, 1992) and International Electrotechnical Committee (IEC, 2004) standards, various standards adopted are presented in Table1. Same sample of oil is used for different thermal ageing test, UV response of oil were analysed. In thermal ageing test maximum temperature maintained is of 100°C and the testing apparatus was provided with air tight sealed environment.

Various modules of test conducted in this work are of

1. Thermal Degradation test on pure transformer oil.
2. Thermal Degradation test on transformer oil along with Press board and Kraft paper.
3. Exclusive Thermal-UV response test on pure transformer oil.
4. Exclusive Thermal-UV response test on transformer oil with Kraft paper and Pressboard.

In case of thermal degradation test, pure oil is subjected to heating hours of 5, 7, 10, 12, 14, 16, 18, 20, 24 and 30. For thermal degradation transformer oil along with insulation Kraft paper and Press board subjected to heating hours of 5, 7, 9, 12, 15, 18 and 20.

In thermal UV visible property analysis of transformer oil, the test is conducted on pure transformer oil and also with the combination of Kraft paper and press board. Based on the index results obtained for bandwidth and absorption peak of various samples of transformer oil we can indirectly determine the level of degradation of transformer oil.

Table 1. Standards for testing.

S.no	Parameters	Testing standards adopted
1	BDV	IS6792 (IS, 1992)
2	Flash Point	ASTM D 3828 (ASTM, 2012a)
3	Fire Point	ASTM D 3828 (ASTM, 2012a)
4	Viscosity	ASTM D 2162-06, IP 70 (ASTM, 2012b)
5	Volume resistivity	IEC 60247 (IEC, 2004)
6	Dielectric constant	IEC 60247 (IEC, 2004)
7	Loss factor	IEC 60247 (IEC, 2004)
8	Acidity	BS 2000 Part 1 (BS, 2010)

Break down voltage is the ability of oil to withstand stresses without failure. Breakdown strength analysis of transformer oil gives effective results through which suitable dielectric material for the related high voltage applications can be explored. The tests are carried as per Indian standard (IS, 1992) specifications. Acidity is a measure of free organic and inorganic acid present in the oil and expressed in terms of milligrams of Potassium Hydroxide (KOH) required to neutralize the total free acids in one gram of oil. Presence of these acid contents in oil causes detrimental to insulation system and leads to corrosion of transformer tank. Acidity level of transformer oil is measured as per British Standard (BS, 2010). Flash point of a volatile liquid is the lowest temperature at which it can vaporize to form an ignitable mixture in air. The Fire point is defined as the temperature at which the vapour continues to burn after being ignited. It is the lowest temperature at which, on further heating beyond the flash point, the sample support and combustion for five seconds. Flash and fire point test is carried out in Pensky-Martens apparatus as per ASTM (ASTM, 2012a).

The perfect dielectric can be represented as lumped perfect capacitance. When a Sinusoidal AC voltage is applied the charging current flowing in the capacitance leads the voltage by angle 90°. However in realistic insulation systems the angle is less than 90° due to losses caused by conduction and polarization current. The complement of angle between voltage and current vectors is called dielectric loss of angle δ or dielectric loss angle. The tangent of this angle δ provides an indication of losses in insulation and is known as Power factor or Dielectric Dissipation factor. The tests are carried out as per IEC standards (IEC, 2004). Viscosity of oil is the measure of transformer oil resistance to shear. Viscosity varies inversely with temperature. Viscosity is measured using Red wood viscometer at the temperature of 30°C. The test is carried out as per ASTM standard (ASTM, 2012b).Various samples of Transformer Oil (TO) for the first two modules of test with their combination of materials are given in the Table 2.

Table2. Samples description.

Sample Name	Description
Sample 1	5h heated TO
Sample 2	7h heated TO
Sample 3	10h heated TO
Sample 4	12h heated TO
Sample 5	14h heated TO
Sample 6	16h heated TO
Sample 7	18h heated TO
Sample 8	20h heated TO
Sample 9	24h heated TO
Sample 10	30h heated TO
Sample 11	5h heated TO with pressboard
Sample 12	7h heated TO with pressboard
Sample 13	9h heated TO with pressboard
Sample 14	12h heated TO with pressboard
Sample 15	15h heated TO with pressboard
Sample 16	18h heated TO with pressboard
Sample 17	20h heated TO with pressboard

Results and discussion

Thermal degradation test on pure transformer oil

Initial test results for pure transformer oil are given in the Table 3. In thermal degradation test all the test samples were heated for 5, 7, 10, 12, 14, 16, 18, 20, 24 and 30 hours. Test is conducted to simulate the real time aging of oil only due to heat source. Maximum temperature maintained inside the apparatus is of 100ºC. Various changes in the critical characteristics like BDV, Flash point, Fire point, UV response, Loss factor, Resistivity, Dielectric constant, Acidity and Viscosity were examined.

Table 3. Initial Sample readings.

Parameters		Value
Acidity (mg KOH gm^{-1})		0.0269
Viscosity(centistokes)		20.06
Breakdown Voltage(kV/2.5 mm)		15
Flash Point(ºC)		160
Fire Point(ºC)		220
U.V.	ABS	0.1479
Response	T %	82.32
Volume Resistivity(Ωcm) (one minute value)		339×10^9
Loss Tangent at 90ºC		0.1444
Dielectric Constant		1.08

Test results for thermal degradation of transformer oil are given in Table 4. Figure 1a shows the variation of acidity to hours of heating. The acidity value increased up to 10 hours of heating from 0.02940 to 0.03457 mg KOH g^{-1}. Heating of pure oil for hours alone does not create acidity, various factors like moisture content and other impurities causes the oxidation of transformer oil thereby increase the level of acidity. The oxidation process continues till the impurities are consumed. The acid level did not increased beyond 10 hours which indicates that all the impurities responsible for oxidative process have been consumed and hence no further oxidation and increase in acidity upon further heating. However from the test results it is conferred that whenever oil is heated up to 30 hours, the level of acid content (0.034 mg KOH g^{-1}-saturated) was up to accepted level as per BS standard (BS 2000 Part 1). Figure 1b shows the variation of viscosity to hours of heating, viscosity value shows a sharp increase at 10 hours of heating and then trends to decrease down rapidly, therefore flow rate of oil get increased.

Figure 1c shows the variation of BDV to hours of heating. BDV gets increased at the initial stage, the reason is the moisture content in oil gets evaporated at initial stage. On increasing the hours of heating it trends to decrease rapidly. Fig.1d shows the variation of Flash point to hours of heating. Flash point variation shows a steady level up to 18 hours of heating, and then its value gets sharp increase in 24 hours of heating, but finally the characteristics shows a steady margin value at 160 to 161ºC.

Figure 1e shows the variation of Fire point to hours of heating. Fire point value characteristics shows a rapid increase for 10 hours of heating and then it tends to lower, finally after 18 hours of heating the value gets saturated in the range of 230ºC.

Figure 1f shows the variation of absorption peak to hours of heating, at the initial stage of heating the characteristics shows a rapid increase and after hours of heating it shows downward trends characteristics. Figure 1g shows the variation of transmission to hours of heating, transmission characteristics of oil shows a rapid increase during initial 12 hours of heating, finally it obtains the level of saturation. Figure 1h shows the variation of Volume resistivity to hours of heating. Volume resistivity at initial stage shows a peak increase, but when the oil is heated the value of volume resistivity trends to decrease. It is conferred that resistivity value of oil reduces on days of heating. Figure 1i shows the variation of loss angle to hours of heating. Dissipation factor value at initial stage shows a higher value but on further heating the dissipation factor value gets decreased. Figure 1j shows the variation of Dielectric constant to hours of heating. Dielectric constant at initial stage gets lowered and then it shows a steady increase. The above test results provide information about characteristics changes of pure transformer oil for different levels of thermal degradation.

Table 4. Thermal Degradation test on transformer oil.

Samples	No. of Hours of Heating (h)	Total acid Value mg KOH g^{-1}	Viscosity (cSt) at 30ºC	Breakdown Voltage kV/2.5mm	Flash point (ºC)	Fire point (ºC)	U.V. Response		Volume Resitivity Ω-cm One minute X 10^9	Loss Tangent at 90ºC	Dielectric Constant
							ABS	T%			
Sample 1	5	0.02940	15.742	25	160	185	0.135	83.50	119	0.385	1.56
Sample 2	7	0.03205	14.253	33	160	190	0.140	83.66	452.36	0.177	0.56
Sample 3	10	0.03457	18.65	23	160	205	0.136	83.46	145.76	0.35	1.54
Sample 4	12	0.03478	17.206	25	160	207	0.132	84.06	123.77	0.36	1.49
Sample 5	14	0.03479	14.253	20	160	200	0.133	84.00	219.89	0.087	0.38
Sample6	16	0.03478	14.201	19	160	187	0.133	83.7	201	0.265	0.76
Sample7	18	0.0336	14.109	20	159	191	0.132	84.01	198	0.301	0.80
Sample 8	20	0.03501	13.109	18	160	192	0.134	83.80	195	0.372	0.81
Sample 9	24	0.03490	13.101	17	161	201	0.133	83.76	188	0.388	1.28
Sample10	30	0.03491	12.789	16	160	203	0.134	84.01	180	0.396	1.51

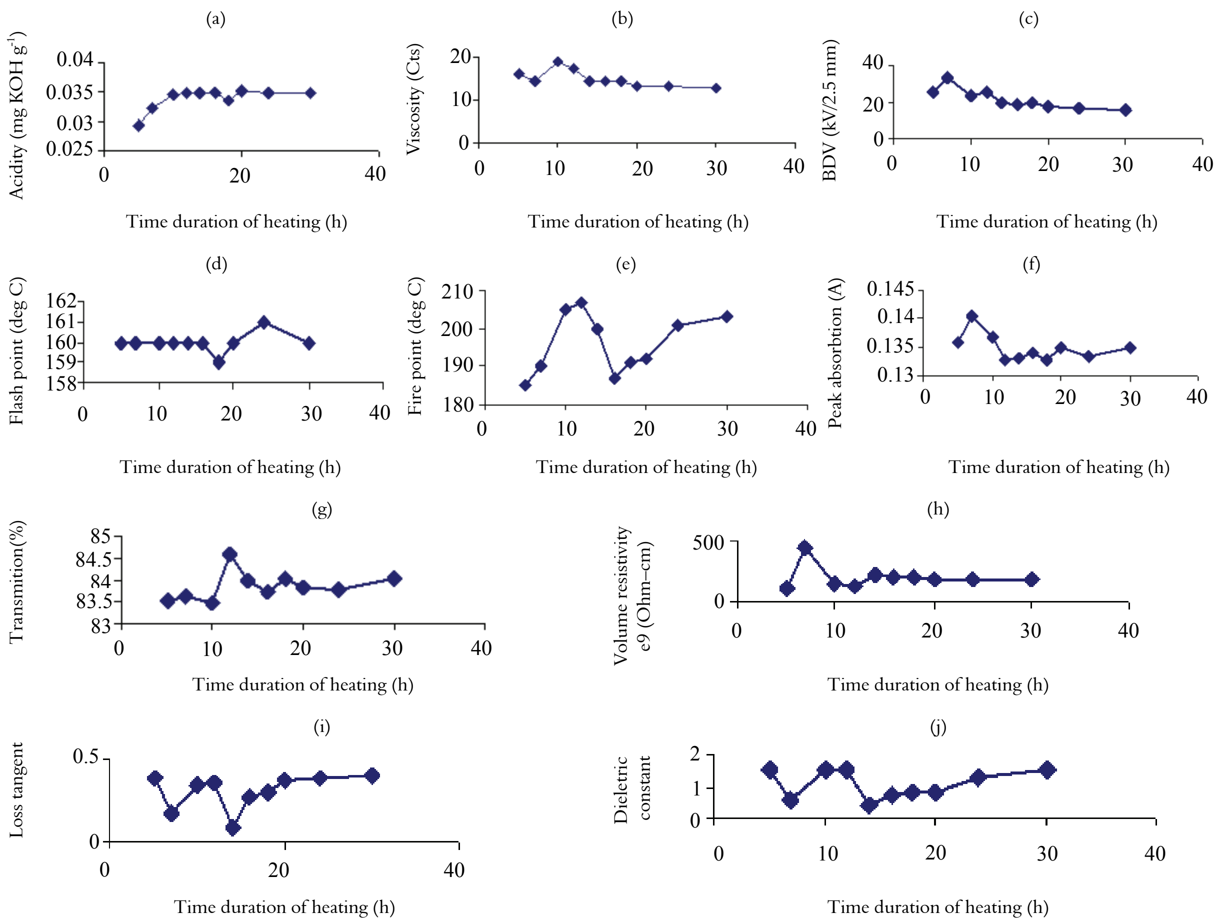

Figure 1. Variation of acidity, viscosity, BDV, Flash point, Fire point, transmission, absorption, volume resistivity, dielectric constant to hours of heating for pure oil. a- Variation of Acidity; b- Variation of Viscosity; c- Variation of BDV; d- Variation of Flash point; e- Variation of Fire point; f- Variation of Absorption; g- Transmission; h-Variation of Volume resistivity; i- Variation of Loss tangent; j- Variation of Dielectric constant.

Thermal degradation test on oil with press board and kraft paper

In this test all the test samples were heated up to 5, 7, 9, 12, 15, 18, 20 hours. Test is conducted to simulate the real time thermal degradation of oil along with deterioration of solid insulation like press board and Kraft paper. The total weight of Press board and Kraft paper mixed along with oil is of 300 gm. Maximum temperature maintained inside the apparatus is of 100°C. Various changes in the critical characteristics like BDV, Flash point, Fire point, UV response, Loss factor, Resistivity, Dielectric constant, Acidity and Viscosity were examined. Test results for Thermal Degradation test on oil along with Press board and paper is given in Table 5.

Figure 2a shows the variation of acidity to hours of heating. Acidity value slowly increase at the initial stage of heating up to 10 hours of heating, after 20 hours of heating it remains unchanged. It shows that acidity value after 30 hours of heating was within the accepted level. Figure 2b shows the variation of viscosity to hours of heating. Viscosity value shows a sharp increase at 7 hours of heating and then trends to decrease down rapidly therefore flow rate of oil gets increased. Figure 2c shows the variation of BDV to hours of heating. BDV gets increases at the initial stage the reason is the moisture content in oil gets evaporated at starting stage. On increasing the hours of heating BDV trends to decrease rapidly.

Figure 2d shows the variation of Flash point to hours of heating. Flash point values at the initial stage gets sharp increase and on further heating it gets reduced. Figure 2e shows the variation of Fire point to hours of heating. Fire point value shows increasing trend characteristics and more or less it attains a saturated value after 15 hours. Figure 2f shows the variation of Absorption peak to hours of heating. At the initial stage the peak absorption value sharply increases up to 9 hours of heating and then it shows a moderate increase. Figure 2g shows the variation of Transmission to hours of heating. Transmission property of oil shows a variation of up and down value, at one stage (18 hours) the value starts to decrease. Figure 2h shows the variation of Volume resistivity to hours of heating. Volume resistivity value obtained in the sample of oil along with press board and Kraft paper is very high compared to characteristics value of pure oil. Volume resistivity at initial stage shows a peak increase, but when the oil is heated the value of volume resistivity trends to decrease. It is conferred that resistivity value of oil reduces on days of heating. Figure 2i shows the variation of Loss angle to hours of heating. Loss factor value obtained in the sample of oil along with press board and Kraft paper is very low compared to characteristics value of pure oil. Dissipation factor value at initial stage shows a higher value but on further heating the dissipation factor value gets decreased. Figure 2j shows the variation of Dielectric constant to hours of heating, the value slowly degrades on increase of hours of heating. The above test results provide information about characteristics changes of pure transformer oil along with Pressboard and Kraft paper for different levels of thermal degradation.

Table 5. Thermal Degradation test on oil along with Press board and Kraft paper.

Samples	No. of Hours of Heating (h)	Total acid Value (mg KOH g^{-1})	Viscosity (cSt) at 30°C	Breakdown Voltage KV/2.5mm	Flash point (°C)	Fire point (°C)	U.V. Response		Volume Resitivity Ω-cm One minute X 10^9	Loss tangent at 90°C	Dielectric Constant
							ABS	T%			
Sample 11	5	0.5142	18.65	17	160	165	0.115	82.7	506.39	0.078	0.33
Sample 12	7	0.8530	22.89	10	170	180	0.143	84.1	2242.23	0.008	0.02
Sample 13	9	0.7462	20.07	16	165	205	0.140	83.7	4002.14	0.006	0.01
Sample 14	12	0.7831	19.09	15	164	202	0.140	84.0	4000.58	0.005	0.01
Sample 15	15	0.8310	18.90	13	163	197	0.140	83.8	3780.00	0.008	0.02
Sample 16	18	0.8309	18.01	13	164	208	0.140	84.7	3500.27	0.008	0.02
Sample 17	20	0.8308	17.02	11	162	203	0.142	84.0	2289.91	0.009	0.01

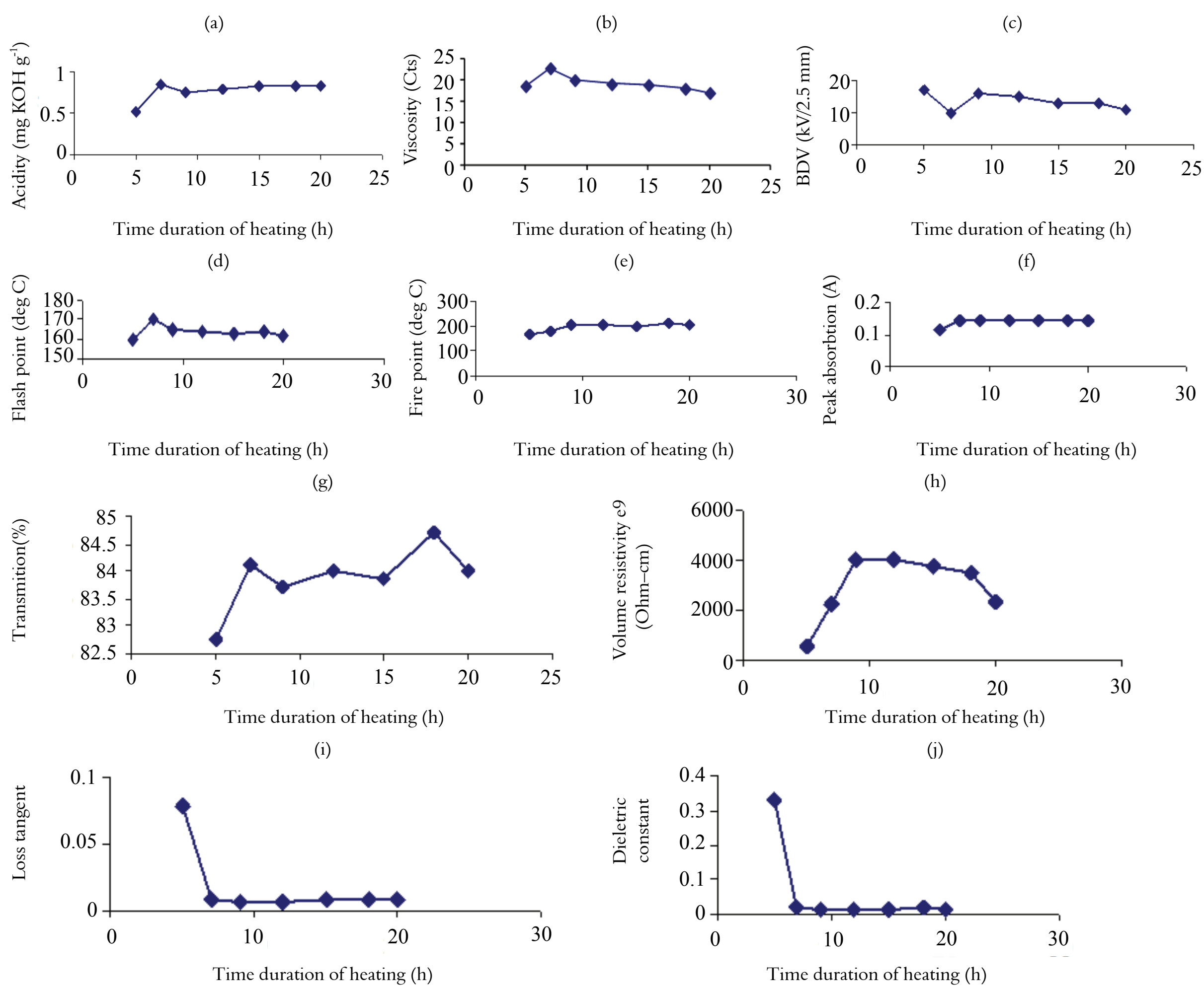

Figure 2. Variation of acidity, viscosity, BDV, Flash point, Fire point, transmission, absorption, volume resistivity, dielectric constant to hours of heating for oil with insulating materials. a- Variation of Acidity; b- Variation of Viscosity; c- Variation of BDV; d- Variation of Flash point; e- Variation of Fire point; f- Variation of Absorption; g- Transmission; h-Variation of Volume resistivity; i- Variation of Loss tangent; j- Variation of Dielectric constant.

Correlations of Electrical parameters of transformer oil with Pressboard and Kraft paper

Correlations among the critical electrical characteristics of oil with press board and Kraft paper were analysed. The test results provide excellent information about the correlation of electrical characteristics like BDV, volume resistivity and loss factor.

Figure 3a shows the variation of loss factor to volume resistivity. Samples with press board and Kraft paper have very highest value of resistivity. It is clearly confirmed that loss factor value steadily decreases for increase of volume resistivity. Figure 3b shows the variation of loss factor to BDV, it is clearly identified that whenever the loss factor increases, the BDV value shows steady decrease. Figure 3c shows the variation of Volume resistivity to BDV. It is clearly recognized that on increase in values of resistivity the with stand capability BDV of transformer oil shows a rapid increase.

Exclusive Thermal-UV response test on Transformer oil

UV-Visible spectrophotometer is used to analyse the transmission and absorption capability of oil. As per IS, IEC, ASTM standards spectral response analysis is not a mandatory test for liquid dielectrics. Experiment is carried out with UV-Visible spectrophotometer having single beam facility. Test is conducted for various hours of heating of pure transformer oil, based on the test results like wavelength and Peak absorption we can determine the level of thermal degradation of oil as an indirect methodology. The wave length of pure transformer oil lies in the UV region (200-300 nm) and test results are presented in Table 6.

Exclusive thermal -UV response test on oil with Kraft paper and press board

In exclusive thermal UV-Visible test pure oil is mixed with kraft paper of weight 10 gm, thickness of 5 mm and press board weight 105 gm, thickness of 4 mm. Kraft paper and Press board on degradation generates furan derivatives such as 5 Hydroxy methyl furan, 5Methyl furan, 2 Acetyl furan and 2 Furaldehyde (2FAL). One of the main furan derivatives is of 2 FAL which is a key factor for determining strength of solid insulation paper. These furan derivatives have the wave length of range 250-380 nm. Based on the test results obtained from Table 6 and 7 it is confirmed that transformer oil spectral response tends to change for various levels of contaminations and degradation level. For pure transformer oil when subjected to thermal degradation test, the wave length lies between 200 to 300 nm and the absorption peak varies based on the level of thermal degradation. For oil with Kraft paper and press board during measurement of absorption peak the wave length lies between 357-372 nm. From the results obtained it is clearly established that bandwidth and absorption capability of transformer oil changes for various level of heating.

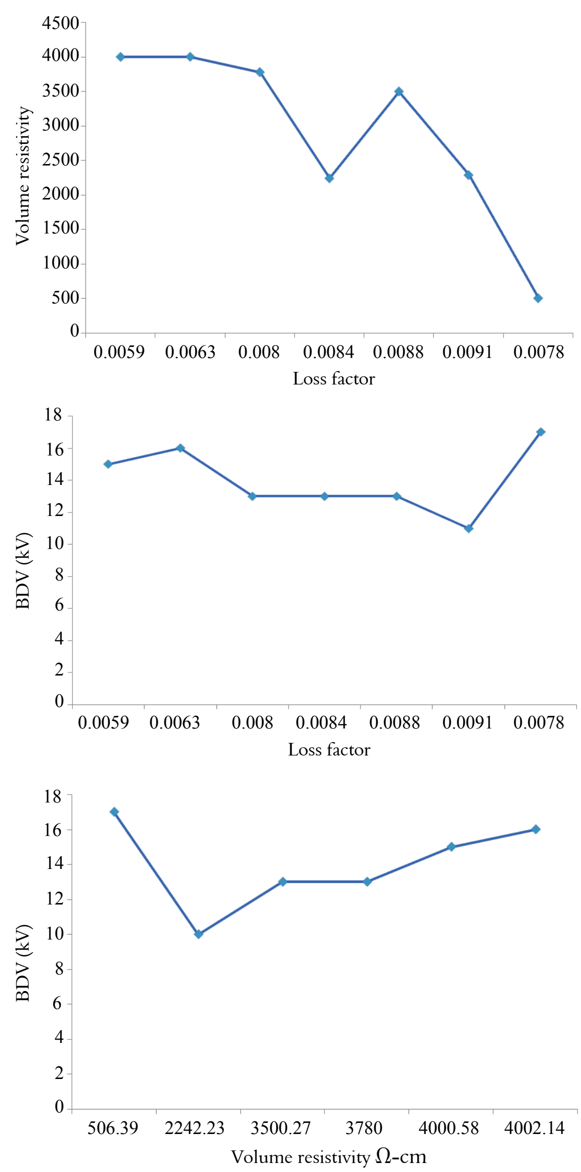

Figure 3. Correlation of electrical parameters BDV, volume resistivity, Loss factor of oil with Press board and Kraft paper. a- Variation of Loss factor to Volume resistivity; b- Variation of Loss factor to BDV; c- Variation of Volume resistivity to BDV.

Table 6. Spectral response of pure transformer oil.

Sample	Hours of heating samples	Bandwidth value (Absorption Maximum) nm	Peak Absorption (A)
Pure Transformer oil	10	220	0.1400
	15	228	0.1511
	20	230	0.1560
	25	235	0.3508
	30	240	0.6090
	40	238	0.9380

Table 7. Spectral response of pure transformer oil with Kraft paper and press board.

Sample	Hours of heating samples	Bandwidth value (Absorption Maximum) nm	Peak Absorption (A)
Transformer oil with Kraft Paper and press board	10	357	0.931
	15	365	0.938
	20	369	0.947
	25	370	1.088
	30	371.4	1.410
	40	377	1.470

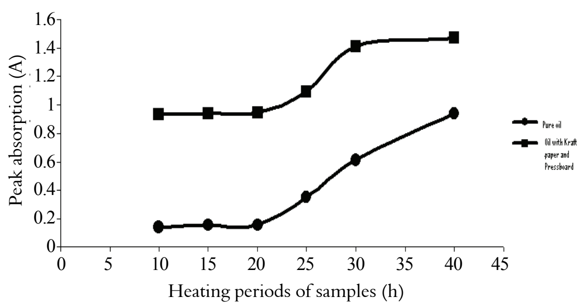

Figure 4. Variation of Absorption peak to hours of heating of samples.

Absorption and bandwidth value differ for increase of contaminants, pure oil has lesser wavelength since it absorbs light in small quantity. From the Figure 4 it is observed that absorption peak of transformer oil with Kraft and pressboard is higher than pure oil, since the insulation materials absorbs more UV light than the pure oil. Whenever contaminants increases, UV-visible light take additional time to penetrate the sample, hence wavelength value also increases. It can be predictable that by knowing the exact peak absorption of oil with range of particular bandwidth confirms the presence of furan derivatives dissolved in oil due to solid insulation deterioration. UV test is not a mandatory test as per standards, but based on more number of experimental results obtained with various levels of degradation, an index value of absorption peak with their corresponding bandwidth can be formed. Based on the index values we can determine the level of contaminants.

Conclusion

Experimental investigations have been carried out on transformer oil with various levels of degradations to study its characteristics changes. Critical parameters of oil is analysed for various level of thermal degradation with combinations of insulation materials. Aging characteristics analyses of transformer oil using spectral response gives some idea towards level of degradation. Correlations among the electrical characteristics were examined and the results were inferred. Effective condition monitoring of transformer oil surely paves way for increased life time of insulation, as a result surprised failure and forced outages shall be minimized.

Acknowledgements

The authors like to thank Department of Science and Technology (DST), Ministry of Science and Technology, Government of India for funding the project to do this research work on “Investigations of critical electrical characteristics and UV response of transformer oil for optimized functions of Power transformer” under Fast track Young Scientists Scheme (SR/FTP/ETA-49/2010).

References

ASTM-American Society of Testing and Materials. **ASTM D 3828** - Standard test methods for determining Flash Point - Fire point for oil. West Conshohocken, 2012a. (Book of Standards Volume: 05.02).

ASTM-American Society of Testing and Materials. **ASTM D 2162-06** - IP 70 Standard test methods and protection rating for determining viscosity of oil. West Conshohocken, 2012b. (Book of Standards Volume: 05.01).

BS-British Standard. **BS 2000 - Part 1** - Methods of Determination of acidity, neutralization value. Englewood, 2010.

HAN, Y.; SONG, Y. H. Condition monitoring techniques for electrical equipments-A Literature survey. **IEEE Transactions on Power Delivery**, v. 18, n. 1, p. 4-13, 2003.

IEC-International Electro Technical Committee. **IEC 60247** - Insulating liquids - measurement of relative

Permittivity and Dielectric dissipation Factor (tanδ) and DC resistivity. Geneva, 2004.

IS-Indian Standard. **IS6792** - Methods for determination of electric strength of insulating oil. Govt. of India, 1992.

KOHTOH, M.; UETA, G.; OKABE, S.; AMIMOTO, T. Transformer insulating oil characteristic changes observed using accelerated degradation in consideration of field transformer conditions. **IEEE Transactions on Dielectrics and Electrical Insulation**, v. 17, n. 3, p. 808-818, 2010.

KOHTOH, M.; KANEKO, S.; OKABE, S.; AMIMOTO, T. Aging effect on electrical characteristics of insulating oil in field transformer. **IEEE Transactions on Dielectrics and Electrical Insulation**, v. 16, n. 6, p. 1698-1706, 2009.

Received on November 3, 2011.
Accepted on January 31, 2012.