An Overview of Electrical and Thermal Analysis of Insulation Properties of Different Transformer Oils

R. Gayathri[1*] , Dr.P.Deiva Sundari[2]
[1]*Assistant Professor, Department of EEE, KCG College of Technology, Chennai, India.*
[4]*Professor/Associate Dean, KCG Collage of Technology, Chennai, India*
[1]gaya3sbrcdm@gmail.com

Abstract—Trends in the field of high voltage engineering show most of the conducted works have focused on the transformer oil such as mineral oil, vegetable oil, oil-based Nano fluids. The average life period of transformer has reduced to half of their designed life due to insulation problem and its 75% of high voltage transformers are caused by insulation failures. Both the life time and functional reliability of transformers mainly depends on the insulating materials. This paper presents an overview and general backgrounds of research and development in the field of different solution methods to obtain the physical and chemical properties of different transformer oil like mineral oil, vegetable oil, oil-based nano fluids found in the literature. Some of the most popular methods that included various testing, analysis method and simulation methods are reviewed and analysed in detail. This paper provides useful guidelines for the future studies for those interested in the problem or intending to do additional research in this area.

Keywords : Nano fluid, Thermal ageing, Breakdown strength, Impulse voltage, Oil-impregnated paper, natural ester, dissolved gas analysis.

1. Introduction

Electrical energy is generated at places where it is easier to get water head, oil or coal for hydro-electric, diesel or thermal power stations respectively. Thus energy is to be transmitted at considerable distances for use in villages, towns and cities located at distant places. Since transmission of electrical energy at high voltage is economical therefore some means are required for stepping up the voltage the generating stations and stepping down the same at the places where it is to be used. Electrical machine used for this purpose is ‘ Transformer’.

In our country the electrical energy is usually generated at 6.6 or 11 or 33 kV stepped up to 132 or 220 kV/400kV with the help of step up transformer for transmission and then stepped down to 66kV or 33kV at grid substations for feeding various substations, which further step down the voltage to 11kV for feeding distribution transformers stepping down the voltage further to 400/230 V for consumer use.

i) Transformers are also used in low power electronic circuits by stepping down the voltage to a suitable level.

ii) These are used in Instrument transformer for protection purpose.

iii) Impedance matching purpose in electronics and control systems.

iv) Isolation of DC maintaining continuity of AC between two circuits

v) Filament transformers to supply power to heat filaments in vaccum tubes, cathode ray tubes in television monitor, computer monitor.

In transformer, transformer oil is used for carrying heat from the core and coils. It also provides additional insulation. Normally mineral oil is used as transformer oil. It is obtained by refining crude petroleum. High dielectric strength, high flash point, low viscosity is some of the essential properties of transformer oil. These properties are abundance in vegetable oil also. So research is done in this area. These properties are also improved by adding Nano fluids with mineral oil or vegetable oil. Transformers are known by different names in different application. The transformer windings and the metallic container are insulated from one another by suitable transformer oil. The transformer oil not only provides insulation but also helps to dissipate the heat due to iron and copper loss occurring in the transformer.

2. Review of literature

This paper gives general backgrounds of research and development in the field of transformer oil in transformer based on 25 published research articles. The following literature presents the summary of testing and the characteristics of transformer oil. The related assumptions made, strengths and weaknesses of each solution methods are highlighted.

1. *Michal Rajnak et.al in 2017 presented "Electrical conduction in a transformer oil-based magnetic nano fluid under a DC electric field"* Experimental study of the direct current electrical conduction in a magnetic nano fluid based on transformer oil and iron oxide nanoparticles stabilized with oleic acid was reported. The current–voltage characteristics of the pure transformer oil and the magnetic nano fluid with various particle volume fractions and electrical conductivity values were calculated. From the experimental study it was discovered that the current–voltage attributes display the converse hysteresis-like behaviour. The remarkable thinning of the current–voltage inverse hysteresis loop was obtained by applying external magnetic field

2. *H. Zakaria et.al in 2017 presented "Characteristics of Mineral Oil-based Nano fluids for Power Transformer Application"* Patterns in the field from claiming nanomaterial-based transformer oil demonstrate the most of the works have focused only on the transformer oil-based nano fluids and the stability of transformer oil-based nano fluids studies were limited. Cold-atmospheric weight plasma technique is suggested to functionally change the silicon dioxide (SiO_2) nano fluids so as to improve the electrical properties of the mineral oil-based nano fluids. It was found that in cold-atmospheric pressure plasma method have higher AC breakdown voltage values than natural oil. Fourier Transform Infrared (FTIR) Spectroscopy also used to study the physical changes of oil.

3. *Chao Tang et.al in 2016 presented "The space charge behaviours of insulation paper immersed by mineral oil and MIDEL 7131 after thermal ageing"* In thermally aged oil-paper in mineral oil and synthetic ester MIDEL 7131space charge impacts were tested and compared. This test indicates that the MIDEL oil-paper may have a better insulation performance than that of the mineral oil.

4. *Muhammad Rafiq et.al. in 2016 presented "Breakdown Characteristics of Transformer Oil Based Silica Nano fluids"* In this study the AC breakdown strength and impulse breakdown strength of mineral oil with SiO_2 nano fluids were conducted in order to find the moisture content and influence of the moisture in AC breakdown strength and impulse breakdown strength and also the modification of nanoparticles to improve the breakdown strength were discussed.

5. *Junko Tkunaga et.al in 2017 presented "Gas Generation of Cellulose Insulation in Palm Fatty Acid Ester and Mineral Oil for Life Prediction Marker in nitrogen-sealed Transformers"* To sample the headspace of a closed thermal aging, a new apparatus was developed. In Aged insulating material in mineral oil and palm fatty acid ester, the gas characteristics were analysed and compared with the gas chromatography method. The possibility of using carbon oxides as a marker for the lifetime of nitrogen-sealed transformers also proved by this research.

6. *U. Mohan Rao et.al in 2017 presented "Physiometric and Fourier transform infrared spectroscopy analysis of cellulose insulation in blend of mineral and synthetic ester oils for transformers"* In this paper in the mixture of mineral and synthetic ester (SE) oils, the cellulose performance were studied. By applying accelerated thermal stresses in the Solid insulation impregnated with mineral oil (MO) and mixture oil in order to find the deterioration rate of cellulose and also the dielectric strength of paper and oil – moisture diffusion in to the paper were also examined. Finally concluded that the performance of cellulose insulation was improved with addition of SE to MO.

7. *A. Narayani et.al in 2017 presented "A Statistical Study on the AC Breakdown Voltage of Corn Oil and Mineral Oil for Liquid Insulation"* In this the investigation made on the corn oil (CO) as alternate liquid insulation to mineral oil (MO). With two parametric distributions (Normal and Weibull distribution) the statistical analysis of breakdown voltage on corn oil was carried out. Breakdown voltage on corn oil as well as mineral oil were conducted, it was found that the corn oil has the suitable and better breakdown characteristics than the mineral oil and hence the corn oil has the potential to

replace traditional mineral oil in high voltage transformer.

8. *Tonglei Wang et.al in 2017 presented "Gaseous characteristics of impulse breakdown initiation process in transformer oil"* In this transformer oil statistical characteristics of the impulse breakdown time lag were studied and the discharge formation time lag were obtained by the Laue's pattern. In this based on the F-N theory the theoretical equation of the statistical discharge lag and the strength of the electric field was proposed and the nucleation time was also calculated based on the vaporization nucleation theory

9. *Zhao Tao et.al in 2017 presented "Breakdown Characteristics of Transformer Oil Insulation under Impulse Voltage with Different Waveform Parameters"* In this the breakdown in transformer oil under the influence of impulse voltages with different waveform parameters for the insulation of the transformer were investigated experimentally. First an impulse voltage generator was built based on the solid state switch and produced different kinds of impulse voltage. Five different impulse voltage waveforms are used: 1.4/50µs, 11/210µs, 0/700µs, 130/1700µs and 250/2600µs. Then the breakdown tests were carried out under these impulse voltages. The results show that the breakdown voltage was closely related to the front time of the impulse voltage, the gap distance and the radii of curvature of the needle electrode. The propagation time of the streamer increases with the increase of the impulse front time, also the breakdown time delay has the same characteristic. The factors that influence the gap breakdown voltage were finally analysed and discussed.

10. *Heli Ni et.al in 2016 presented "Study on Impulse Breakdown Characteristics in Transformer Oil with Different Electrode Materials"* In this the 50% impulse breakdown voltages and the discharge time delay with different metal electrode materials like copper-tungsten , stainless steel, copper and aluminium were obtained through experiments and also Weibull distribution functions and the Laue plots were obtained. From the results it was observed that the average breakdown electrical field with different electrode materials were different especially copper-tungsten were the largest, followed by stainless steel, copper and aluminium. From the Laue plots the average statistical time lag and the average discharge formation time were derived and the differences were discussed. Existences of two parallel discharge processes were proved by the appearance of the inflection point in Laue plot.

11. *Bai mei Wang et.al presented "Thermal aging results between oil-paper insulation impregnated by mineral and vegetable insulating oil"* thermal aging experiments carried out on oil-paper insulation involved insulating paper, mineral insulating oil, vegetable insulating oil and the mixed insulating oil, which is combined by vegetable and mineral insulating oil with different proportions. A mass ratio of the vegetable insulating oil to the mineral insulating oil in mixed insulating oil gives the proportion of vegetable and mineral insulating oil (PVM). The experiments were conducted at 130°C to analyse the aging products characteristics of different types of oil-paper insulation samples. From the experimental result, acid value and furfural content of insulating oil also increased with aging time. These parameters were also based on the PVM of mixed oil. So it is advantages to fill the vegetable oil in the transformer instead of mineral oil

12. *F.Guerbas et.al in 2016 presented "Thermal aging effect on the properties of new and reclaimed transformer oil"* In this paper thermal ageing effect studied on three kinds of oil new mineral oil, reclaimed used oil and re-reclaimed aged oil. These three oils are kept under 100oC in different aging times. According to specifics standards the physicochemical and electrical analysis were carried out. In this breakdown voltage decrease in new oil due to the presence of copper and paper lead in the new oil. This comparative study also explained the thermal stability behaviour of three kinds of oil used.

13. *Natalia Zhuravleva et.al in 2016 presented "The Study of Thermal Aging Components Paper- Impregnated Insulation of Power Transformers"* This paper examined the optical, electrical and mechanical properties and heat stability of the components of paper-impregnated insulation of power transformers. By doing the process of thermal aging the spectral transmission characteristics of liquid dielectrics and the tangent of dielectric loss angle were measured. This paper concluded that the Transformer fluid MIDEL 7131 under thermal aging showed better stability than the oil of type GK.

14. *XIA Guoqiang et.al in 2017 presented "Study on The Aging characteristics of Transformer Oilpaper Insulation Based on Improved Time Domain Dielectric Spectroscopy"* By using time domain dielectric spectroscopy, the polarization/depolarization current of Samples were found by carried out the thermal aging test. By using wavelet transform theory, an algorithm was developed for improving time domain dielectric spectroscopy. The improved wavelet transform algorithm can effectively improve the time domain dielectric spectrum, thus the main polarization processes of oil-paper insulation is clearly shown in the time domain dielectric spectroscopy.

15. *Shuai Li et.al in 2016 presented "Study on Ageing Characteristics of Insulating Pressboard Impregnated by Mineral-Vegetable Oil"* In this paper the thermal aging characteristics of pressboards impregnated by mixed oil containing pure mineral oil (80 vol%) and vegetable oil (20 vol%) were studied. It was found that the degree of polymerization (DP) of the mixed-oil pressboard sample A was decreased more slowly than that of the pure mineral oil-pressboard sample B with the aging time the n the dielectric properties of the samples were measured in the frequency range 10-1 Hz-106 Hz. It was found that the dielectric loss tanά of sample A increased more slowly than that of sample B with the thermal ageing. The breakdown field of the two samples keeps at nearly the same level in the thermal ageing process. This paper concluded that the mixture oil-pressboard insulation may be a potential alternative to the traditional mineral oil-pressboard insulation used in the power transformer.

16. *Yan-Hui Wei et.al in 2015 presented "Partial Discharge Characteristics and Trap Parameters of Aged Oil-impregnated Paper"* The life of power equipment was affected by the degradation of oil-impregnated paper induced by partial discharge (PD). PD characteristics and trap parameters of the impregnated paper were measured to find the relationship between partial discharge and the degradation of oil-impregnated paper. For each sample, phase resolved partial discharge (PRPD) spectrograms were recorded then the characteristics of partial discharge were analysed, and the trap parameters of specimens were obtained by the thermally stimulated depolarization current (TSDC) method. Following this, the microstructures of the samples were observed using a scanning electron microscope (SEM)

17. *Yuanwei Zhu et.al in 2017 presented "Origin of Dielectric Processes in Aged Oil Impregnated Paper"* Deterioration of Oil impregnated paper in power transformers in long-term operation leads to dielectric characteristics variations. In this paper the investigation on distinguishing dielectric processes can be done and its mechanism was obtained to promote further details on oil impregnated paper and provide guidance for insulation design in power transformers.

18. *Youping Tu et.al in 2016 presented "Moisture Migration in Oil-impregnated Film Insulation under Thermal Ageing"* Due to thermal degradation, moisture produced in the insulating material of the transformer causes damage to the insulation system. In this three types of samples Kraft insulation paper, PC and PET film, were impregnated in oil and thermally aged under 90, 110 and 130 °C respectively. This concluded that the moisture content produced by polymer is much more than that by oil, and most of the moisture is absorbed by the sample surface. The ageing temperature has considerable influence on the moisture migration in polymers.

19. *Chao Tang et.al in 2016 presented "The space charge behaviours of insulation paper immersed by mineral oil and MIDEL 7131 after thermal ageing"* Surface charge effects were tested in thermally aged oil-paper. In this studies mineral oil and synthetic ester MIDEL 7131 immersed paper, were tested and compared. In MIDEL 7131immersed paper, the conductivity has been increased which leads to decrease of charge accumulation. The Max. electric field distortions of different oil-paper samples indicate the MIDEL oil-paper may have a better insulation performance than that of the mineral oilpaper.

20. *A. Sbravati, K. Rapp et.al in 2017 presented "Transformer Insulation Structure for Dielectric Liquids with Higher Permittivity"* Normally mineral oil have been the standard solution for transformers for the last hundred years, both in distribution and power transformers. In this mineral oil was replaced by natural ester oil. The permittivity of natural ester liquid was around 40% higher than that of mineral oil, while the permittivity of pressboard and paper made from kraft pulp, I impregnated with natural ester liquids is just slightly higher.

21. *Taufik Widyanugraha et.al in 2015 presented" DGA and Tensile Strength Test on Accelerated Thermal Aging of Ester Oil and Kraft Paper"* This paper stated that experimental results on chemical and mechanical properties of ester oil and kraft paper under accelerated thermal aging process. 800ml ester oil plus10 kraft paper are put in each of seven hermetical bottles and subjected to thermal aging at 120oC and 150oC.Dissolved gas analysis and tensile strength measurement was conducted after aging time of 336 hours, 672 hours and 1008 hours. The experimental results showed total amount of dissolved gases increase with increasing temperature and the duration of aging.

22. *F.Guerbas et.al in 2017 presented "Comparative Study of Transformer aged oil Reclamation by Fuller's earth and activated Bentonite"* This paper indicates that the type of adsorbents is very important for reclamation process. Thermal ageing has been carried out in transformer oil by using two types of adsorbents such as fuller's earth and activated bentonite. It can be concluded from the test result that activated bentonite treated transformer aged oil shows a best result than that one treated by fuller's earth. Moreover Bentonite activated by sulphuric acid leads to improve its adsorbents power. But its activation parameter should be well chosen. So bentonite provides a good treatment of aged transformer oil with its environmental and economic advantages.

23. *Li-Shuang Cao et.al in 2015 presented "Dielectric Performance of Silicone Oil-paper Composite Insulation System under Thermal Aging"* Silicone oil is also used as a insulating fluids where we need fireproofing and environment protection In this paper, the chemical and dielectric performance of silicone oil-paper composite insulation system under thermal aging is discussed. Mineral oil-paper and silicone oil-paper were tested. It concludes that acidity content and dielectric loss were much lower in silicone oil than in mineral oil and AC breakdown voltage was higher in silicone oil than in mineral oil.

24. *M. M. Ariffin et.al in 2017 presented "Ageing Effect of Vegetable Oils Impregnated Paper in Transformer Application"* In this paper both vegetable oils and mineral oil with impregnated Kraft paper Dielectric properties, mechanical properties and chemical properties were investigated and compared. A breakdown voltage in vegetable oil much higher than mineral oil but dielectric loss was less in mineral oil than vegetable oil. For the same temperature level vegetable oil possess higher relative permittivity than the mineral oil. Viscosity of mineral oil lowest compared to the vegetable oils. But the acidity is higher in vegetable oil than mineral oil. In mineral oil acidity was same throughout the aging process.

25. *BIN DU et.al in 2012 presented "Preparation and Breakdown Strength of Fe3O4 Nano fluid Based on Transformer Oil"* To enhance the dielectric properties of transformer oil, stable nano fluid of Fe3O4 nanoparticles with different concentration in the transformer oil were prepared using Hexadecyl trimethyl ammonium Bromide (CTAB) as surfactant. The results indicated that the addition of Fe3O4 nanoparticles to transformer oil can enhance its dielectric strength .

3. Conclusion

In this paper, an overview and key issues of different research studies for transformer insulating material is presented. The transformer oil has attracted many researchers' attention recently due to its physical and chemical characteristic such as high breakdown strength, less moisture, high corona inception voltage etc. The results showed an improvement in breakdown strength of Nano fluids with respect to that of base transformer oil. It is clear, from the existing literature, that there are different solution methods for physical and chemical characteristic of insulating material in transformer oil. To improvise physical and chemical characteristic of insulating material in transformer oil such as mineral oil, vegetable oil, oil-base nano fluids provided helpful information and references for researchers can lead additional studies in this field.

References

1. Y.Z. Lv, Y. Zhou, C.R. Li, Q. Wang, B. Qi, Recent progress in nanofluids based on transformer oil: preparation and electrical insulation properties, IEEE Electr. Insul. Mag., Vol. 30, pp.23–32,2014.

2. C.Tang, G.Chen,M.Fu, and R.Liao, Space charge behaviour in multilayer oil-paper insulation under different DC voltages and temperatures, IEEE Transactions on Dielectrics and Electrical Insulation,Vol. 17, No. 3, pp. 775-784, 2010.

3. Y. Jing, I. V. Timoshkin, M. P. Wilson, M. J. Given, S. J. Macgregor, T. Wang, and J. M. Lehr, Dielectric properties of natural ester, synthetic ester Midel 7131 and mineral oil Diala D, IEEE Transactions on Dielectrics and Electrical Insulation,Vol. 21, No. 2, pp. 644–652, 2014.

4. CIGRE, Effect of particles on dielectric strength, working group of 17 committee, 12 June 2002.

5. Methods for the determination of the lighting impulse breakdown voltage of insulating liquids, IEC 60897 (1987).

6. J.K. Nelson and J.C. Fothergill, Internal charge behavior of nano composites, Nanotechnology, Vol. 15, pp. 586-595, 2004.

7. K.J. Rapp and C.P. McShane, Review of Kraft paper/natural ester fluid insulation system aging, IEEE Int'l. Conf Dielectr. Liquids, pp. 1-4, 2011.

8. L. E. Lundgaard, W. Hansen and S. Ingebrigtsen, Ageing of mineral oil impregnated cellulose by acid catalysis, IEEE Trans. Dielectr. Electr.Insul., Vol. 15, pp. 540-546, 2008.

9. ASTM E228–11: Standard test method for linear thermal expansion of solid materials with a push-rod dilatometer, 2011

10. Liao, R.-j., Tang, C., Yang, L.-j., Thermal aging micro-scale analysis of power transformer pressboard, IEEE Trans. Dielectr. Electr. Insul., Vol.15,No.5, pp. 1281–1287, 2014.

11. Rudy Setiabudy, Abderrahmane Beroual, Setijo Bismo and Henry B.H. Sitorus, Comparison of Statistical Breakdown Voltages in Jatropha Curcas Methyl Ester Oil and Mineral Oil Under AC Voltage, IEEE International Conference on the Properties and Applications of Dielectric Materials,Vol.4, No.1,pp. 528-531, 2015.

12. S. Senthil Kumar, M. Willjuice Iruthayarajan and M. Bakrutheen, Analysis of vegetable liquid insulating medium for applications in high voltage transformers, IEEE International Conference on Science, Engineering and Management Research, ICSEMR., pp. 1-5, 2014.

13. Ushakov, Vasily Y., Viktor Fedorovič Klimkin, and S. M. Korobeynikov. Impulse breakdown of liquids. Springer Science & Business Media, 2007.

14. Jones, Haley M., and Erich E. Kunhardt. Evolution of cathode initiated pulsed dielectric breakdown in polar and nonpolar liquids. Conduction and Breakdown in Dielectric Liquids, 1996, ICDL'96, 12th International Conference on. IEEE, 1996.

15. Y. Kamata, A. Miki, S. Furukawa, A singular flashover path observed on the surface of synthetic-resin-bonded paper cylinders immersed in transformer oil under switching impulse voltage conditions, IEEE Transactions on Electrical Insulation, Vol.26, pp.300-310, Apr il 1991.

16. P. Rain, O. Lesaint, Prebreakdown phenomena in mineral oil under step and ac voltage in large-gap divergent fields, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.1, pp.692-701, August 1994.

17. O. Lesaint, G. Massala, Positive streamer propagation in large oil gaps. IEEE Transactions on Dielectrics and Electrical Insulation, Vol.5, No.3, pp. 360-370, 1998.

18. K. C. Kao, J. B. Higham, The effects of hydrostatic pressure, temperature, and voltage duration on the electric strengths of hydrocarbon liquids. Journal of the Electrochmical Society, Vol.108, No.6, pp. 522-528, 1961.

19. D. Martin, I. Khan, J. Dai and Z. D. Wang, An overview of the suitability of vegetable oil dielectrics for use in large power transformers, TJIH2b Euro TechCon Can!, Chester, UK, pp. 1-20,2006.

20. J. Li, Z.T. Zhang, P. Zou, S. Grzybowski, M. Zahn, Preparation and Experimental Investigation of Breakdown and Dielectric Properties of Vegetable-Oil-Based Nanofluid, IEEE Electrical insulation Magazine. Vol.28, No.5, pp.43-50, 2014.

21. D. Martin, Z. D. Wang, P. Dyer, A. W. Darwin and I. R. James, A comparative study of the dielectric strength of ester impregnated cellulose for use in large power transformers, IEEE int'!. Can! Solid Dielectr., Winchester, UK, pp. 294-297, 2007.

22. Liao R, Liang S, Sun C, Yang L, Sun H. A comparative study of thermal aging of transformer insulation paper impregnated in natural ester and in mineral oil. European Transactions on Electrical Power, Vol.20, No.4, pp.518–533, 2010.

23. J.S. N'cho, I.Fofana, A.Beroual, T.Aka-Ngnui and J.Sabau, Aged oil Reclamation: Facts and Arguments Based on Laboratory, IEEE Transactions on Dielectrics and Electrical Insulation, Vol.19, No. 5; October 2012.

24. Subbiah Deepa, R. Sarathi, Ashok K. Mishra, Synchronous fluorescence and excitation emission characteristics of transformer oil ageing, Talanta, Vol. 70, No. 4, pp. 811–817,2006.

25. Zhengzhen Zhou, Zhanfei Liu, Laodong Guo, Chemical evolution of Macondo crude oil during laboratory degradation as characterized by fluorescence EEMs and hydrocarbon composition, Marine Pollution Bulletin, Vol. 66, pp. 164–175, 2013.

26. Liao Ruijin, YANG Lijun, ZHENG Hanbo, et al. Reviews on Oil-Paper Insulation Thermal Aging in Power Transformers,. Proceedings of CSEE, Vol.27, No.5, pp.1-12, 2012.

27. LIAO Ruijin, GUO Pei, ZHOU Nianrong, et al. Influence of Water Content and Aging on Temperature Domain Dielectric Spectroscopy and Activation Energy of the Transformer Oil Impregnated Papers[J]. High Voltage Engineering, Vol. 40, No.5, pp.1407-1415, 2012.

28. S.Q. Wang, J.L. Wei, S.S. Yang, M. Dong, G.J. Zhang and X.W. Liu, Frequency domain dielectric spectroscopy characteristics of oil-paper insulation under accelerated thermal aging, Proc. Chin. Soc. Electrical Eng., Vol. 34, pp.125-131, 2010.

29. R.J. Liao, J. Hao and G. Chen, A comparative study of physicochemical, dielectric and thermal properties of pressboard insulation impregnated with natural ester and mineral oil, IEEE Trans. Dielectr. Electr. Insul., Vol.5, pp.1626–1637, 2011.

30. T.R. Blackburn, Z. Liu, R. Morrow and B.T. Phung, Partial Discharge Development in a Void and its Effect on the Material Surface, IEEE 6th Int'l. Conf. Properties and Applications of Dielectr. Materials, Xi'an, China, pp: 280-285, 2000.

31. K. Temmen, Evaluation of surface changes in flat cavities due to ageing by means of phase-angle resolved partial discharge measurement, J. Phys. D: Appl. Phys., Vol. 33, pp. 603–608, 2000.

32. K. Yang., Aging Characteristics Research of Polymer Material in Mineral Oil under Thermal Aging, M.Sc. diss., North China Electric Power University, Beijing, China, 2013.

33. M. Yao, Textile Materials Science, China Textile & Apparel Press: Beijing, pp. 43-50, 2009 (in Chinese).

34. W. Wang, Z. Ma, C. Li and X. Wang, Impact of Cellulose Aging on Moisture

Equilibrium of Oil-pressboard Insulation Proceedings of the Chinese Society for Electrical Engineering (CSEE), Vol. 32, pp. 100- 105, 2012.

35. V. M. Montsinger, Loading Transformer by Temperature, Trans. American Institution of Electrical Engineers, Vol. 49, No.2 p.776-792, 1930.

36. M. Fukuma, M. Nagao, M. Kosaki, and Y. Kohno, Measurements of conduction current and electric field distribution up to electrical breakdown in two-layer polymer film, in Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Vol. 2, pp. 721–724,2000.

37. K. C. Kao, Electrical conduction and breakdown in insulating polymers, in Proceedings of the 6th International Conference on Properties and Applications of Dielectric Materials, IEEE Dielectrics and Electrical Insulation Society, Xi'an, China, pp. 1–17,2000.

38. T. Prevost, M. Franchek, K. Rapp, Investigations of the dielectric design criteria for pressboard/natural ester interfacial stress, 75th Int. Conf. Doble Clients, April 6-11, Paper IM-3, Boston USA, 2008.

39. K.J. Rapp, J. Corkran, C. P. McShane, T. A. Prevost, Lightning Impulse Testing of Natural Ester Fluid Gaps and Insulation Interfaces, IEEE Trans. Dielectrics and Electrical Insulation, Vol. 16, No. 6, pp. 1595-1603, 2009.

40. Y. Abe, M. Kozako, H. Toda, M. Tsuchie, M. Hikita, E. Sasaki, Dissolved Gas Analysis of Transformer Oil Under the Conditions of Partial Discharge and Overheating, Proc. : International Conference on Condition Monitoring and Diagnosis, A4-5, pp. 131 – 134, 2010

41. John Voukelatos, Kostas Argiropoulos, Peter Stenborg, and John Luksich, Natural Ester (Vegetable Oil) Dielectric Fluid Application in Transformers, Cooper Power Systems - McGraw-Edison Development Corp., 19 Mykinon Street, GR-166 74 Glyfada, Athens, Greece.

42. F.Guerbas, L.Adjaout, A.Abada, D.Rahal, Thermal aging effect on the properties of new and reclaimed transformer oil, IEEE International Conference on High Voltage Engineering and Application, ICHVE September 19-22, Chengdu, China,2016.

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

44. Mohammed R.Meshkatoddini, Aging study and lifetime estimation of transformer mineral oil, American J. of Engineering and Applied sciences Vol.1, No.4, pp.384-388, 2008.

45. Abdul Rajab1, Aminuddin Sulaeman, Sudaryatno Sudirham & Suwarno, A Comparison of Dielectric Properties of Palm Oil with Mineral and Synthetic Types Insulating Liquid under Temperature Variation, Vol.3, No.2, 2008.

46. Jung-Il Jeong, Jung-Sik An and Chang-Su Huh, Accelerated Aging Effects of Mineral and Vegetable Transformer Oils on Medium Voltage Power Transformers, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 19, No. 1, 2012.

47. H. Kan, T. Miyamoto, Y. Makino, S. Namba and T. Hara, Absorption of CO2 and CO Gases and Furfural in Insulating Oil Into Paper Insulation In Oil-immersed Transformers, IEEE Int'l. Sympos. Electr. Insul., Pittsburgh, PA, USA, 41-44, 1994.

48. D. Allan, Recent Advances in the Analysis and Interpretation of Aged Insulation from Operating Power Transformers, IEEE 5th Int'l. Conf. Properties and Applications of Dielectr. Materials (ICPADM), Seoul, Korea, pp. 202-207, 1997.

49. C. D. Xue, Monitoring paper insulation aging by measuring furfural contents in oil, 7th Int'l. Sympos. High Voltage Eng., pp.139–142, 1991.

50. W. Lu, Q. Liu and Z.D. Wang, Gelling Behaviour of Natural Ester Transformer Liquid under Thermal Ageing, IEEE Intern. Conf. High Voltage Engineering Application (ICHVE), Shanghai, China, pp. 643-647, 17th - 20th Sept, 2012.

51. Q. Liu and Z.D. Wang, Streamer characteristic and breakdown in synthetic and natural ester transformer liquids under standard lightning impulse voltage, IEEE Trans. Dielectr. Electri. Insul, Vol. 18, pp. 285-294, 2011.

52. C. Perrier, M.-L. Coulibaly, and M. Marugan, Methanol as a New Ageing Marker of Oil-Filled Transformer Insulation, presented at the 23rd International Conference on Electricity Distribution - CIRED, Lyon, 2015.

53. E. Rodriguez-Celis, S. Duchesne, J. Jalbert, and M. Ryadi, Understanding ethanol versus methanol formation from insulating paper in power transformers, Cellulose, Vol. 22, pp. 3225-3236, 2015.

54. C. Perrier and A. Beroual, Experimental investigations on insulating liquis for power transformers: mineral, ester and silicone oils, IEEE Electr. Insul. Mag., Vol. 25, 2009, pp. 6-13.