

# *Effect of Aromatics and Polar contaminant of natural ester oil on dielectric strength and breakdown time in mineral oil under lightning impulse voltage excitations*

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**Abstract**—Mineral oil forms a backbone in the transformer having the main role of dielectric, coolant and diagnostic due to its good physical, thermal and chemical performances with low cost and wide availability. The chemical composition of insulating oil is a main key factor in impulse breakdown voltage and time to breakdown. Therefore, an effort has been made to investigate the effect of aromatics and polar contaminants on impulse withstand voltage and time to breakdown of mineral oil. This effect is studied under positive and negative polarity of impulse in the extremely nonuniform field for electrode gap between 1mm to 10mm. In addition, to analyze the effect of aromatics, two different types of mineral oils, paraffinic inhibited mineral oil (contains predominantly paraffinic chain structure) and naphthenic inhibited mineral oil (contains a higher proportion of cyclic structures and aromatics compared to paraffinic oils). Further, to examine the effect of polar contamination in mineral oil, natural ester oil (highly polar in nature) is mixed with mineral oil which is highly non-polar in nature. The lightning impulse withstand voltages of natural ester oil and mixture oil are deduced and compared with mineral oil to analyze the effect of aromatics and polar contaminants.

**Keywords**—Impulse breakdown strength, aromatics, natural ester, mixture oil, time to breakdown

## I. INTRODUCTION

Mineral oil is a mixture of liquid hydrocarbons having several molecular structures such as naphthenic, paraffinic, and aromatic. Aromatic molecules are entirely different from paraffinic and naphthenic molecules in terms of chemical and physical properties [1-4]. Generally, aromatic molecules are cyclic and planar structures having a ring of resonance bonds with alternating double bonds which gives better stability to molecules (for example Benzene ring) [2-4]. In earlier research papers it is mentioned that the breakdown strength of mineral oil reduces with an increase in aromatic content under negative impulse voltage excitations [4-5]. It indicates that the aromatic ring has an important role in dielectric strength and breakdown time of insulating oil under impulse conditions. It is not mentioned in the literature that how this effect will vary the electrode gap and while applying positive impulse voltage. It will give

an idea to predict the effect of aromatics under both positive and negative impulse waveshape polarities with various electrode gaps of 1mm to 10mm.

Nowadays, natural ester oils are becoming highly popular as a potential alternative of mineral liquid used in environmentally critical and fire critical applications [6-8]. The electro-negativity of the O<sub>2</sub> (oxygen) in natural ester liquid turns the ester liquid to have more polar than mineral oil, which will aggravate the electrification due to oil flow and may result in space charge issues. Since the physical and chemical properties of natural ester oil are different from mineral liquid, the oils should not get mixed to avoid contaminants either at a factory while manufacturing the transformer or during maintenance activity at the site [4, 5, 9-10]. Generally, natural ester liquid is miscible with mineral liquid in all proportions if it is accidentally mixed [9, 10]. The mixing of natural ester oil and mineral oil may also happen at the time of the retro filling process if the residual mineral oil is not removed properly. The mixtures of two different oils may also exhibit different dielectric behavior, thermal performance and chemical compositions. This gave the motivation to evaluate the breakdown voltage of mineral oil after the addition of polar contaminant (natural ester oil) to it.

A significant amount of research has been carried out to predict the breakdown phenomena of natural ester liquid and mineral liquid under impulse condition and power frequency operating conditions [2-8]. This paper focuses on the evaluation of the behavior of mineral oil with aromatic content; paraffinic inhibited mineral oil is compared to naphthenic inhibited mineral liquid for the negative and positive polarity of impulse waveshape. The paraffinic inhibited mineral liquid used in the experiment contained no aromatics while the naphthenic oil contains cyclic carbon and aromatics rings. Further to evaluate the effect of polar contaminant, a mixture of inhibited paraffinic mineral liquid and natural ester liquid is selected. The mineral liquid is non-polar in nature than natural ester oil.

Mineral oil named Transol, produced by Savita Oil Technologies Limited and natural ester oil named BioTransol produced by Savita polymers limited are used in this work. These liquids are compared and their impulse dielectric strengths are predicted. Further impulse strengths of pure liquids (mineral oil and natural ester oil) and a mixture containing 10% natural ester in mineral oil are evaluated to analyze the effect of polar contaminants.

## II. CHEMICAL STRUCTURE OF LIQUID INSULATIONS- REVIEW FOR EXPERIMENTAL CONSIDERATIONS

### A. Mineral oil

Mineral oil is produced from hydrocarbons obtained from crude oil through different methods of distillation, refining and purification process. It contains various hydrocarbons molecules with different structures of open-chain paraffin ( $C_nH_{2n+2}$ ), saturated ring systems of naphthenes ( $C_nH_{2n}$ ) and aromatics ( $C_nH_{2n-6}$ ). The main important difference in chemical structures between naphthenic and paraffinic oil is the presence of complex aromatic structures in naphthenic oils [2-4, 9-10]. In general, the highly refined naphthenic oil contains aromatic content varying from 4 to 10%. Aromatics are chemically different from saturated paraffinic and cyclo-paraffins since aromatics rings have planar structures with alternating double bonds in resonance to provide good stability to structures. This aromatic ring is rich in delocalized pi electrons which can be expected to influence their electrical properties during lightning impulse voltage excitations. Mineral oil contains some amount of aromatic sulphur compounds that could act as natural antioxidants and inhibit oxidation by scavenging free radicals [2-4]. These are classified as uninhibited oils containing only natural antioxidants. In addition, to enhance the oxidative degradation of mineral oils, synthetic inhibitors are added which also act as free radical scavengers to prevent oxidation and enhance the life of oils. They are called as inhibited oils. Thus, mineral oil can also be classified as uninhibited and inhibited oil based on whether it has synthetic inhibitors or not. Naphthenic based mineral oil has a higher solubility for oxidation products, a lower pour point and a higher density than paraffin-based oils. In this paper, two grades of mineral oils are considered concerning the negative and positive polarity of impulse waveshape.

### B. Natural Ester oil

Natural ester liquid is extracted from vegetable seeds (natural plants). Natural ester originated from glycerol and fatty acids which are known as triglycerides. The length of the fatty acid chains of these triglycerides could be from  $C_{12}$  up to 22 carbon atoms and the chains can be both saturated and unsaturated [2-4]. The fatty acids are made up of straight chains having carbon atoms of even number. The presence of saturated fatty acids will provide more anti-oxidation stability of the oil. It will lead to high viscosity value, and the increase in oil viscosity will degrade the cooling capability of natural ester oil [9,10]. The natural ester oil with more unsaturated fatty acids has lower viscosity value but reduced anti-oxidation stability. Hence, the ratio between saturated and unsaturated fatty acids in a natural ester should be optimized. The properties of natural ester oil like viscosity and oxidation stability are balanced optimally for good performance.

## III. EXPERIMENTAL DESCRIPTION

### A. Impulse Generator Specifications

W-S test systems make impulse generator capable of generating the impulse voltage up to 280 kV and having energy 1.96kJ, set at a two-stage, is utilized to provide the required test voltages. The general specification of impulse waveshape is made through the waveshape front (rise time) and time duration is taken to reach the value of 50% value of tail (tail time). The lightning impulse waveshape duration is 1.2  $\mu$ s/50  $\mu$ s with allowed tolerance values of

$\pm 30\%$  and  $\pm 20\%$  on the rise and tail times respectively. A capacitive voltage divider is utilized to measure the applied impulse voltage of both positive and negative polarity. The breakdown voltage and breakdown time are recorded by a Tektronix make DPO 2014 at a sampling rate of up to 1G Sample/s. The breakdown time is measured in  $\mu$ s from the origin of an impulse wave until it falls to zero voltage after the breakdown.

### B. Testing Method

In this study, to evaluate the breakdown voltage of insulating oil under positive and negative polarities, continuous and progressive stress regime is adopted with a constant step increment of applied impulse voltage till the breakdown voltage is achieved. This method is known as the rising voltage method and it is as per ASTM D3300 having 3shots/step [10,11]. The initial voltage ( $U_{Initial}$ ) is 60-70% of the expected breakdown voltage. Time interval ( $\Delta T_1$ ) between 2 consecutive shots is maintained 1 to 1.5 minutes for both the types of mineral oil and mixture oil whereas it is kept between 1.5 to 2.5 minutes for ester oil. Further, a time interval ( $\Delta T_2$ ) between two experiments is 10 to 15 minutes for mineral oil and mixture oil whereas for ester oil time is 15-20 minutes. After every two experiments, the sample is changed. Also, the time interval between two voltage levels in the same experiment that is wait time is 2 to 2.5 minutes for mineral liquid and mixture liquid whereas for ester oil wait time is increased to 3-4 minutes to diffuse gas bubbles and discharge by-products. The following procedure is adopted for every gap distance between 1mm to 10mm and every insulating oil ten breakdown voltages are measured and after that average breakdown voltage is calculated for each case.

### C. Sample Preparation of Mixture of oil

To prepare an oil mixture of mineral oil and natural ester, 10% natural ester liquid (by weight) is mixed with 90% of paraffinic inhibited mineral oil (by weight) at 40°C with the help of a magnet-based stirrer for about 30 min. To verify the miscibility (homogeneous mixture) of natural ester oil with mineral liquid, the mixture is prepared and left to stand for 5 hours without disturbance. After the rest time, a homogeneous clear mixture is observed visually. This is referred as mixture oil in this paper.

Before taking oils for impulse test, a common procedure of sample preparation is followed to reduce the impact of impurity on the results. Firstly, after taking samples from sealed barrels, the test sample is heated in a beaker to reduce its viscosity and to make the easier flow of samples through a filtration unit. For mineral oil, the sample is heated up to 50-60°C and for ester oil, this temperature lies between 100-120°C because it has a higher viscosity than mineral oil. Secondly, this heated sample is purified with the help of the Whatman filter paper, of size 0.45 micrometer under vacuum. The purified oil is again heated at 60°C for mineral oil and 110°C for ester oils in a heating mantle under a vacuum of 760mmHg to extract moisture parameters and dissolved gases from the purified sample. The sample after the above three processes is cooled for 4-5 hours under vacuum only to avoid any interaction of oil samples with the atmosphere. After this a part of the sample is taken to measure all the basic properties of insulating like AC breakdown voltage, water content, viscosity, relative permittivity etc are shown in Table I maintained before the impulse test.

TABLE I PROPERTIES OF PROCESSED OIL SAMPLES USED FOR IMPULSE BREAKDOWN EXPERIMENTS

Properties	Mineral liquid	Natural Ester liquid	Mixture liquid
Breakdown voltage in kV for 2.5mm gap	65-70	70-80	75-85
Water contents in PPM	4-5	55-70	12-14
Loss Factor @ 90°C	0.0022	0.2	0.0027
Relative permittivity	2.2	3.3	2.31
Viscosity at 40°C in mm <sup>2</sup> /sec	8.83	32	9.55

#### D. Electrode Specifications and Test Cell

Electrodes used to perform impulse tests are designed according to ASTM D3300. The ground electrode is made up of polished steel or brass sphere of 0.5 inches (12.7 mm) in diameter whereas the HV electrode is a steel phonograph needle with a specification of 0.06 mm  $\pm$ 20 % radius of curvature. The cuboidal test cell is considered in order to ensure experimentally established value of impulse voltage of liquid due to several gaps with various polarities [13]. This testcell made up of high dielectric strength material (i.e. Acrylic), has an oil capacity of 1L. All the sides of the impulse test cell walls are made of transparent acrylic to examine the breakdown phenomena. The distance between HV and low voltage electrodes in the test cell can be adjusted in steps of 0.5 mm using screw gauges on both electrode terminals.

### IV. EXPERIMENTAL RESULTS

#### A. Effect of Aromatics on Impulse Breakdown Voltage

“Fig. 1” shows the average breakdown strength of paraffinic uninhibited mineral oil and naphthenic inhibited mineral oil in nonuniform configuration for the negative and positive polarity of impulse.

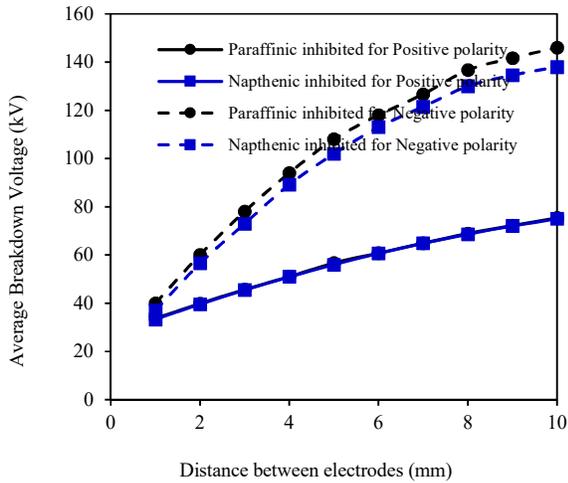


Fig. 1. The average breakdown voltage of Paraffinic inhibited and Naphthenic inhibited Mineral liquid under negative and positive impulse in nonuniform field configuration

From “Fig. 1”, the followings points are observed.

- Under positive polarity, impulse breakdown voltages of paraffinic inhibited and naphthenic inhibited mineral oil are comparable. It indicates that there is no effect in

impulse breakdown voltage due to aromatics present in mineral oil.

- Under negative polarity, the dielectric voltage of naphthenic inhibited mineral oil is slightly lower as that to paraffinic inhibited mineral liquid. In other words, there is an effect of aromatics under negative polarity.

#### B. Effect of Aromatics on Time to Breakdown

“Fig.2” shows the time to breakdown of paraffinic inhibited mineral oil and naphthenic inhibited mineral liquid in nonuniform configuration for both the polarities of impulse.

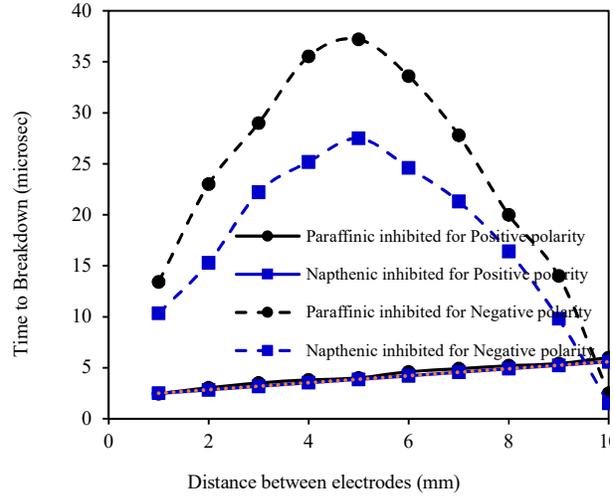


Fig. 2. Time to breakdown of Paraffinic inhibited and Naphthenic inhibited Mineral liquid under negative and positive impulse in nonuniform field configuration

From “Fig. 2”, the followings points are observed.

- Under positive polarity, time to breakdown of paraffinic inhibited and naphthenic inhibited mineral oil is comparable. It indicates that there is no effect in time to breakdown of mineral oil due to aromatics.
- Under negative polarity, the trend of the time to breakdown in paraffinic inhibited mineral oil and naphthenic inhibited mineral oil is similar but the time to breakdown for naphthenic inhibited mineral oil is lesser as compared to that of for paraffinic inhibited mineral oil. Therefore, there is an aromatic effect under negative polarity.

#### C. Effect of Polar Contaminant on Breakdown Voltage

“Fig. 3(a)” and “Fig. 3(b)” shows the average breakdown strength of mineral liquid, natural ester, and mixture liquid in nonuniform design under negative and positive polarity of impulse respectively.

From “Fig. 3(a)” and “Fig. 3(b)” the following points are observed.

- Under positive polarity, impulse breakdown strengths of the mixture and mineral oil are comparable. It indicates that there is no effect on dielectric voltage due to 10% of natural ester oil in mineral oil.
- Under negative polarity, the impulse dielectric voltage of the mixture is significantly less as compared to mineral oil. In other words, the mixture is following the same trend as a pure natural ester.

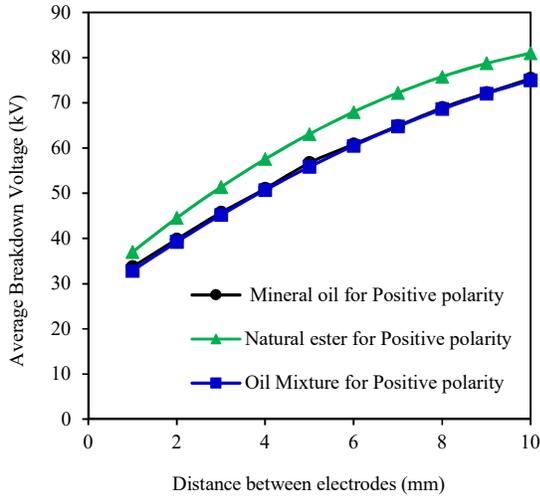


Fig. 3(a) The average breakdown voltage of Mineral, Natural ester and Mixture oil under positive polarity of impulse in nonuniform field configuration

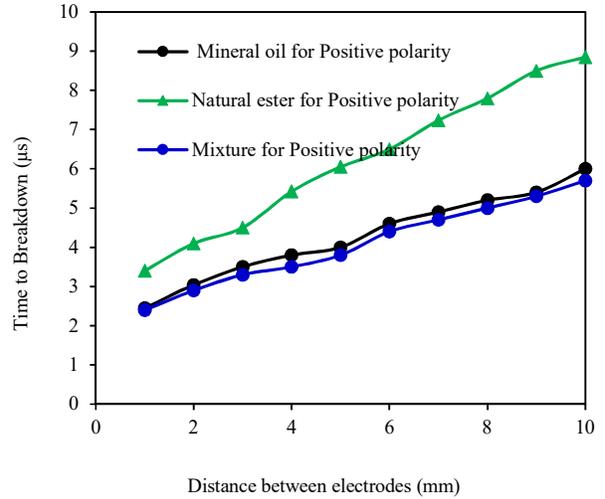


Fig. 4(a). Time to breakdown of Mineral, Natural ester, and Mixture oil under positive polarity of impulse in nonuniform field configuration.

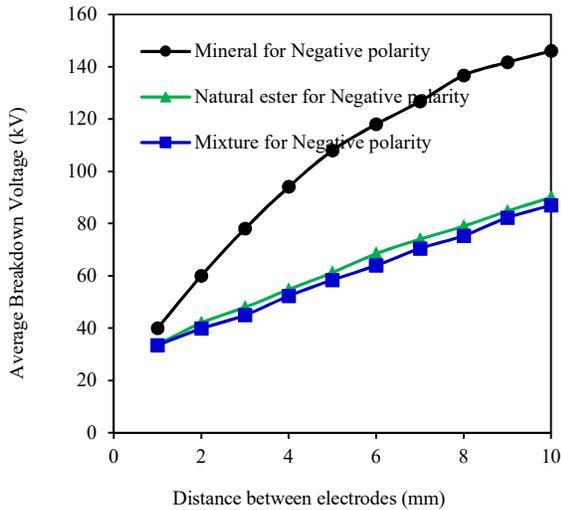


Fig. 3(b) The average breakdown voltage of Mineral, Natural ester and Mixture oil under negative polarity of impulse in nonuniform field configuration

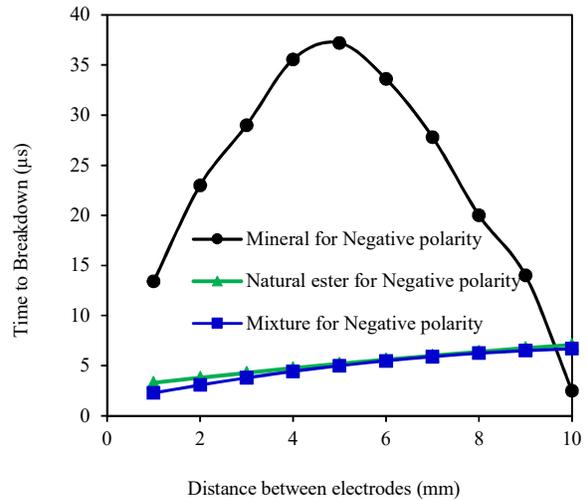


Fig. 4(b). Time to breakdown of Mineral, Natural ester and Mixture oil under negative polarity of impulse in nonuniform field configuration

#### D. Effect of Polar Contaminant on Time to Breakdown

“Fig. 4(a)” and “Fig. 4(b)” shows the time to breakdown of mineral oil, natural ester oil, and mixture oil in nonuniform design under negative and positive polarity of impulse respectively.

From Figures 4(a) and 4(b), followings points are observed:

- Under positive polarity, time to breakdown of the mixture and mineral oil is comparable. It indicates that there is no effect in breakdown time due to 10% of natural ester oil in mineral oil.
- Under negative polarity, it is observed that the mixture is not at following the basic trend of the time to breakdown of mineral oil. Whereas the trend of the time to breakdown in the mixture oil is similar to the trend of breakdown time in natural ester oil.

#### V. CONCLUSIONS

Experimental results point out the effect of aromatics and polar contaminants in mineral oil is observed only with respect to the negative polarity of impulse and not in positive polarity impulse in nonuniform field configuration with respect to impulse breakdown strength as well as breakdown time. Due to the presence of aromatic content in mineral oil, impulse dielectric strength and breakdown time of mineral oil slightly decreases only under negative polarity. In addition, there is no effect under positive polarity. Whereas, the mixture of oil (mineral oil with 10% natural ester oil) behaves like a typical natural ester oil in terms of breakdown strength and breakdown time under negative polarity in nonuniform field configuration.

The studies also indicate that in case, if a mineral oil-filled transformer gets mixed with natural ester oil during vacuum filtration, then the mineral oil-filled transformer may fail in the negative impulse test which is an undesirable effect.

## REFERENCES

- [1] M. Eklund, "Mineral insulating oils; functional requirements, specifications and production," IEEE International Symposium on Electrical Insulation (ISEI), Toronto, Canada, pp. 68-72, 2006.
- [2] X. Wang, "Partial discharge behavior and breakdown mechanisms of ester transformer liquids under ac stress," Ph.D. dissertation, School of Electr. and Electronic Eng., The University of Manchester, UK., 2011.
- [3] Q. Liu, "*Electrical performance of ester liquids under impulse voltage for application in power transformers*," Ph.D. dissertation, School of Electr. and Electronic Eng., The University of Manchester, UK., 2011.
- [4] Wu Lu, "*Prebreakdown and breakdown phenomena of alternative transformer liquids under lightning impulse voltages*," Ph.D. dissertation, School of Electr. and Electronic Eng., The University of Manchester, UK., 2015.
- [5] E. O. Forster, "Critical assessment of the electrical breakdown process in dielectric fluids," IEEE Trans. Dielectr. Electr. Insul., vol.20, no. 4, pp. 891–896, Oct. 1985.
- [6] J.K. Nelson, "An assessment of the physical basis for the application of design criteria for dielectric structures," IEEE Trans. Electr. Insul., vol. 24, no. 5, pp. 835 – 847, Oct. 1989.
- [7] E. O. Forster, "Progress in the field of electrical breakdown in dielectric fluids," IEEE Trans. Dielectr. Electr. Insul., vol. 20, no. 6, pp. 905–912, Dec. 1985.
- [8] A. Beroual, and R. Tobazeon, "Prebreakdown phenomena in liquid dielectrics," IEEE Trans. Electr. Insul., vol. 21, no.4, pp. 613–627, Aug. 1986.
- [9] Dhruvesh M. Mehta, P. Kundu, V. K. Lakhiani and A. S. Jhala, "A review of critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part I", IEEE Transactions on Dielectrics and Electrical Insulation, Vol.23, Issue 2, pp. 873 – 880, 2016.
- [10] ASTM D 3300, "*Dielectric breakdown voltage of insulating oils of petroleum origin under impulse conditions*," 1994.
- [11] ASTM D-3300, "Standard test method for dielectric breakdown voltage of insulating oils of petroleum origin under impulse conditions", ASTM International, West Conshohocken, PA, 2012
- [12] W. Hauschild, and W. Mosch, "*Statistical techniques for high-voltage engineering*" J. W. Arrowsmith Ltd., 1992, Bristol, UK.
- [13] H.P Moser, and V. Dahinden, "*Transformerboard II*", H.Weidmann AG Rapperswil, 1987.