Lightning impulse polarity effect in ester oils and mineral oil for transformer applications

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***Abstract*—Ester oil is becoming increasingly popular as a potential alternative to mineral oil due to eco-friendly, fire safety and higher continuous over loading capability in comparison to conventionally used mineral oil. The high interest on ester oil has led to several studies aimed at prediction of their dielectric breakdown voltage for transformer applications. In this paper, to evaluate the effectiveness of ester oil as a dielectric for transformers the withstand voltages of ester oil under both positive and negative polarities of lightning impulse waveshape in comparison with mineral oil are evaluated for various oil gaps using statistical analysis. In addition, the variation of streamer velocity with various gap distances between electrodes in mineral oil, natural ester oil and synthetic ester oil under different polarity of impulse are extracted to analyze the streamer behavior in ester oil. Finally, the ratios of breakdown voltage, streamer velocity of ester oil with respect to mineral oil are calculated from the experimental results under both positive and negative polarities which serves as a point of reference for insulation design of transformer. Sphere-needle electrode configuration is used to create nonuniform field under lightning impulse stress. The breakdown voltage is determined by multiple level test method and best estimate of 3-parameter Weibull distribution is used for 1% breakdown probability due to breakdown voltage.**

Keywords*—*Mineral oil, Ester oil, Statistical distribution, Nonuniform field, Impulse withstand voltage

I. INTRODUCTION

Dielectric liquid used in power system equipment are generally nonpolar in nature. At present, crude oil based mineral oil is used for more than a century. The dielectric liquid forms a backbone in transformer insulation systems having the main role of insulation, heat transferring agent. Hence, a significant amount of research has been performed on breakdown phenomena of mineral oil in different electric field configurations [1-4]. Recently, the ester oil is becoming increasingly popular as a potential alternative to mineral oil for transformer applications. The technical challenge in the usage of ester oil is that their insulating properties are different from mineral oil and it might change the design, manufacturing and impregnation process of transformer. Since, the chemical compositions and molecular structure of ester oil is different from mineral oil it becomes an imperative to understand the behavior of oil and their impact on transformer insulation design.

A lot of research has been reported in the literature to compare chemical, physical, and electrical properties of ester oil with mineral oil [5-10]. The evaluation of dielectric breakdown of ester oil is one of the important criteria to utilize the ester oil for transformer application under lightning impulse excitations since impulse test is one of the major factory tests to ensure the strength of insulation systems of transformers. Lightning impulse strength as basic insulation level (BIL) is important for the insulation designing of transformer. Therefore, the dielectric breakdown voltage of ester oil is predicted in this paper under lightning impulse test.

Generally, the negative lightning impulse breakdown voltage of mineral oil reduces with increase in aromatic content. It indicates that the chemical composition and intrinsic properties of insulating oil is a key factor in influencing its impulse breakdown voltage [11, 12].Therefore, objective of this paper is to investigate ester oil with various gap distances under different polarities of lightning impulse stress for transformer application in order to consider ester oils as an alternatives for mineral oil. Sphere-needle electrode configurations are used in this study to create nonuniform local electric fields due to lightning impulse voltage excitations. The nonuniform electric field configuration of sphere-needle is chosen to simulate a situation where initiation of discharge takes place locally by insulation faults within the transformer [11-14]. 1% failure probability is estimated using Weibull distribution for various gaps between 1 to 20mm.

II. EXPERIMENTAL DESCRIPTION

A. Generation of Impulse Voltage and Testing Procedure

A two stage impulse generator of peak voltage 280 kV and having energy 1.96kJ is used to generate the standard impulse 1.2(±30%)/50(±20%)µs of both positive and negative polarity. The standard lightning impulse waveform with different polarity is applied across sphere-needle electrode with oil gap between 1mm to 20mm. The applied impulse voltage and time to breakdown are measured by using a digital phosphor oscilloscope (Tektronix make DPO 2014) at a sampling rate of up to 1G Sample/s.

In this paper, measurement of dielectric strength of different insulating oil is performed under progressive stress regime where the impulse voltage is applied across the sphere-needle electrodes. It increases the voltage step by step with a specified voltage step increment. The impulse voltage level is increased by 3shot/step with increment of 1-5kV depending on the electrode gap distance or assumed breakdown voltage (Fig.1). The starting voltage level is set at about 60% to 70% of the assumed breakdown voltage. The time duration between two consecutive shots at the same voltage levels is maintained to 1 to 1.5 minutes for mineral oil and 1.5 to 2.5 minutes for ester oil. The waiting time between two voltage levels is 2 to 2.5 minutes for mineral oil and for ester oil wait time is increased by 3-4 minutes to diffuse gas bubbles and discharge by-products. According to ASTM D 3300,IEC 60897 standards, oil sample is changed after each breakdown though streamer propagation is relatively insensitive to the normal contamination level of water and particle in a strongly nonuniform (divergent) field under lightning impulse conditions [15].

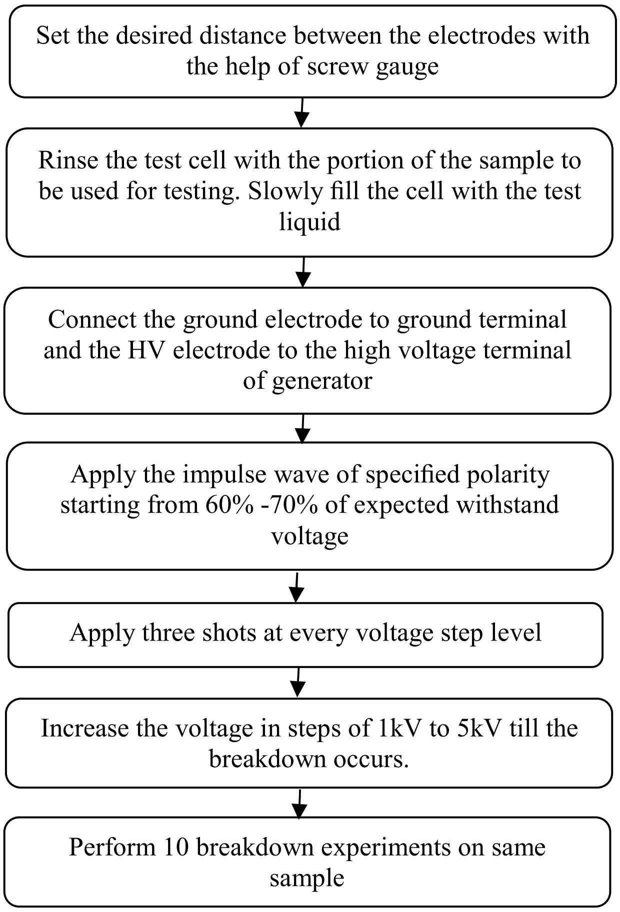

Fig.1. Flow chart of testing procedure to evaluate the breakdown voltage of insulating oil for transformers

B. *Insulating Liquids, Electrodes Specifications and Test Cell under Impulse Test*

In this paper, three types of insulating oils (mineral oil, natural ester oil and synthetic ester oil) are examined for transformers under lighting impulse conditions. The most widely used insulating oil in transformers is petroleum based mineral oil. The mineral oil contains a mixture of naphthenic, paraffinic and aromatic structures. Mineral oils can be classified as uninhibited or inhibited oil based on presence of anti-oxidants. The natural ester oil is derived from natural plants like vegetable seeds. Synthetic ester oil is manufactured synthetically by reaction of petaerythritol with several saturated fatty acids. It provides an oxidatively stable molecule structure. A natural ester has unsaturated fatty acids which accounts for their lower oxidation stability. While the mineral oil, Transol, is manufactured by Savita oil technologies limited, Mumbai, Natural ester oil Biotransol and synthetic ester oil Transol Synth100 are manufactured by Savita polymers limited at Mahad. In all experiments mineral oil is considered as the benchmark for comparison of lightning impulse waveshape polarity effect in ester oil due to several of gap distance between the electrodes.

In a nonuniform configuration, the maximum electric field is dependent on the tip radius rather than the gap distance. Hence, to avoid the influence of tip radius and tip point length, steel phonograph needle of tip radius 0.06mm (±20%) is used as the high voltage electrode. The sphere terminal electrode having diameter of 12.7mm is made up of brass. The electrode gap distance in the test cell can be set in steps of 0.5 mm with the help of screw gauges on either side of the electrode terminals.

Cuboidal test cell is fabricated to establish an experimentally confirmed and statistically supported value of breakdown voltage of oil due to various gaps with different polarities. The sides of test cell are made up of acrylic material with transparent vision in order to observe breakdown phenomena. The quantity of test cell is 1 litre.

C. *Pre-processing of Liquid Samples under Test*

The breakdown voltage of any insulating oil is its ability to withstand the electric stress during transient overvoltage and normal operating conditions and it is mainly dependent on quality of insulating oil [9]. Therefore, moisture and particle content are carefully controlled and are comparatively low in fresh insulating oil. But due to slow ageing and contamination from environment the quality may deteriorate during transportation process or long term storage of oil. To avoid this degradation for the strongly nonuniform field tests, the oil is transported and stored in an opaque barrel sealed under nitrogen to create inert atmosphere. The received oil from drum are filtered by Whatman filter paper of pore size 0.45 µm. The filtered samples are degassed and dehydrated at 100^{o}C for 2 hours under vacuum at 500 mmHg and allowed to further dry the sample. After dehydrating the entire oil, sample is kept for 24 hour to cool down at room temperature under vacuum conditions before performing the impulse testing. Karl Fisher titration equipment is used to determine the moisture content in the oils. The initial properties of the oil samples like AC breakdown voltage at 2.5mm gap, water content and relative saturation are evaluated prior to impulse test (Table I).

Table I. PROPERTIES OF PROCESSED OIL SAMPLES USED FOR IMPULSE BREAKDOWN EXPERIMENTS

Properties	**Mineral oil**	**Natural ester oil**	**Synthetic ester oil**
Breakdown voltage in kV for 2.5mm gap	65-70	70-80	70-80
Water contents in PPM	4-5	55-70	55-70
Relative saturation in %	10	7	7

III. EXPERIMENTAL RESULTS

A. *Evaluation of Average and Standard Deviations of Breakdown Voltage*

Generally, the winding insulation (inter turn, inter disc) and between the winding of transformer are subjected to voltage stresses due to high frequency nature of transient overvoltage as well as continuous operating voltage [13]. Hence, strength of the insulation arrangement between the winding as well as inter disc insulation is predominantly decided by strength of oil gap due to lower permittivity of mineral oil [13, 14]. Therefore, pressboard barrier (solid insulation) is used to subdivide the long oil gaps into smaller oil gaps to reduce the oil stress [13]. In addition to its role of solid pressboard insulation as a dielectric barrier, it also provides mechanical strength and support to winding under different force. The relative permittivity of ester oils (3.3) is about 50% higher than mineral oil (2.2).The ratio of permittivity between solid insulation barriers to oil is lower for ester oil. Hence, the transformer insulation designer therefore has to evaluate the oil gaps created by pressboard barriers for ester oil with respect to mineral oil. Therefore, the present study focuses on evaluating impulse withstand voltages of ester oil only in the limited range of oil gaps from 1mm to 20mm.

Generally, the characteristic of breakdown field of liquid dielectric is estimated from dispersion of the breakdown data due to its stochastic nature. Hence, comparative study of ester oil and mineral oil under positive and negative polarity of lightning impulse involved the evaluation of the mean breakdown voltage and standard deviation of breakdown voltage for different oil gaps. The dispersion of the breakdown data is assumed to follow normal distribution. Tables II and III show the statistical results of mineral oil, natural ester oil and synthetic ester oil in nonuniform field configuration under positive and negative polarity of impulsewave shape respectively.

Table II. STATISTICAL RESULTS OF MINERAL OIL, NATURAL ESTER OIL AND SYNTHETIC ESTER OIL UNDER POSITIVE POLARITY

Statistical values	**Gap in mm**	**Positive polarity of impulse wave shape**		
		Mineral oil	***Natural ester oil***	***Synthetic ester oil***
Average breakdown value in kV	1	34	38	46
	5	57	65	87
	10	75	82	130
	15	105	108	133
	20	129	130	137
Standard deviations in kV	1	2.1	2.5	2.3
	5	2.8	2.8	2.4
	10	5.8	2.3	2.2
	15	4.5	2.7	2.5
	20	3.5	2.8	2.6

From Table II, the following points are observed regarding breakdown values under positive impulse polarity.

- The mean breakdown voltage of mineral oil is less with respect to natural ester oil and synthetic ester oil. In addition, the breakdown voltage of mineral oil and natural ester oil is comparable for the oil gap above 10mm. Though, the percentage difference in breakdown voltage is less between mineral oil and natural ester oil for above 10mm, but standard deviation is higher for mineral oil.
- The standard deviation of mineral oil is high for above 5mm gap with respect to natural ester and synthetic ester oil.

Table III. STATISTICAL RESULTS OF MINERAL OIL, NATURAL ESTER OILS AND SYNTHETIC ESTER OIL UNDER NEGATIVE POLARITY

Statistical values	**Gap in mm**	**Negative polarity of impulse wave shape**		
		Mineral Oil	***Natural Ester Oil***	***Synthetic Ester Oil***
Average breakdown value in kV	1	46	36	43
	5	103	62	85
	10	146	90	129
	15	149	98	133
	20	151	113	139
Standard deviations in kV	1	2.1	2.3	2.4
	5	3.4	2.5	2.6
	10	5.5	3.7	2.3
	15	5.7	3.4	2.5
	20	5.6	3.8	2.7

From Table III, the following points are observed under negative impulse polarity.

- The mean breakdown voltages of mineral oil are higher than ester oil. The percentage difference is less between mineral oil and synthetic ester oil compared to that between mineral oil and natural ester oil.
- The standard deviation of mineral oil is high for above 3mm gap than both the ester oils. Between the two ester oils, synthetic ester oil has lower standard deviations.

From the Table II and III, the ester oil with lesser standard deviation provides a good reproducibility in the impulse withstand voltage for design guidelines evaluations.

B. Estimation of 1% Failure Probability Voltage

Weibull distribution is the best function to explain the behaviour of breakdown data at low probabilities than normal and Gumbel distribution [11,16]. It estimates the combination of statistical parameters based on the fitted curve with specific shape, scale and threshold, which fit the breakdown data with different failure probability values. In this context, the application of 3-parameter Weibull distribution gives a better choice for engineers to indicate at which level of low probability (1%failure probability or less) the designed insulation structure will breakdown. Hence 3-parameter Weibull distribution plots of the breakdown results are obtained under various oil gaps and different polarities.

"Fig.2" shows 3-parameter Weibull distribution plots of dielectric breakdown voltage data of mineral oil, natural ester and synthetic ester oil for the gap of 10mm under positive and negative impulse voltage. In "Fig.2", solid line shows the results of 3-parameter Weibull distribution based on 10 impulse breakdown voltage values obtained from experiments. Generally, the more breakdown test are carried out to obtain large sample size for predicting the withstand voltage. However, performing more number of experiments, becomes expensive and time-consuming. In addition, it is only valid if the breakdown voltage of the test oil is not influenced by any by-products of frequent breakdowns [11-14, 16]. It is observed during experiments that there is a good repeatability in the results of breakdown data and therefore considering time constraint 10 sample points are used to evaluate the failure probability voltage. The correlation coefficients of the breakdown data points when fitted to the Weibull function are given along with 3-parameter Weibull distribution parameters (shape, scale, and threshold) and 95% confidence bounds. The dashed line shows upper and lower confidence level at 95% confidential line.

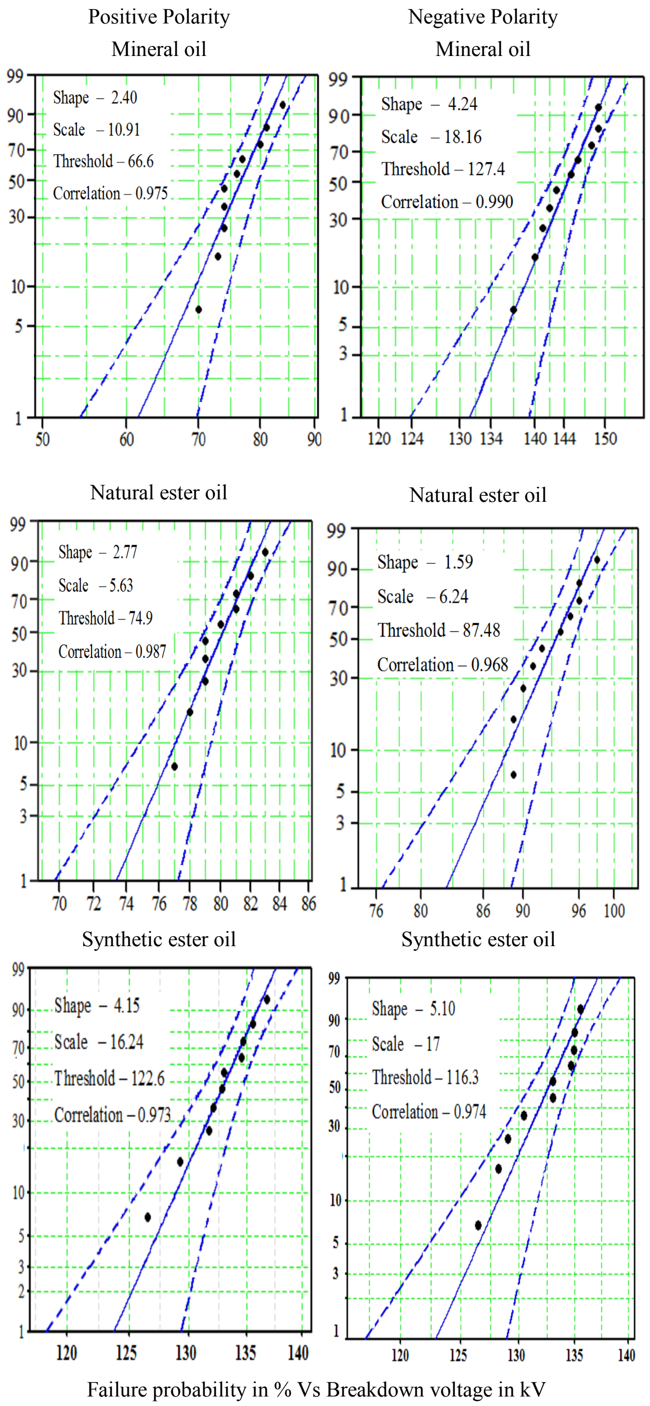

Fig.2. Weibull distribution of impulse breakdown data under positive and negative polarity for 10mm gap.

C. Evaluation of Impulse Withstand Voltage and Effect of Impulse Polarity on Withstand Voltage

The withstand voltage of oil is predicted generally from intersection of Weibull distribution curve fitting and the 1% failure probability rate. From the predicted results of Weibull distribution, 99% withstand voltage (1% failure probability) of mineral oil, natural ester and synthetic ester oil are extracted from Weibull distribution analysis and it is shown in "Fig.3". "Fig.3" shows results on the analysis of breakdown tests using Weibull distribution of 1% failure probability voltage for mineral oil, ester oils under positive polarity and negative polarity of lightning impulse.

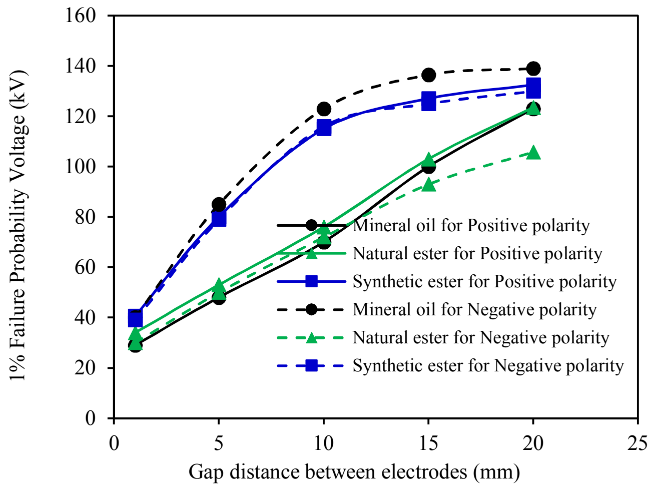

Fig. 3. 1% failure probability voltage of mineral oil, natural ester and synthetic ester oil under positive and negative polarity of impulse.

From "Fig.3" following points are observed on application of nonuniform field configuration.

- Under positive impulse, impulse withstand voltage of synthetic ester is much higher than mineral oil and natural ester oil. Whereas, impulse withstand voltage of mineral oil and natural ester are comparable.
- Under negative impulse, impulse withstand voltage of mineral oil is significantly higher compared to ester oil for above 5mm oil gap. Among ester oils, synthetic ester has much higher withstand voltage than natural ester oil.
- In mineral oil, polarity effect is evident as the impulse withstand voltage in negative polarity is much higher than positive polarity. However, only slight polarity effect is observed in natural ester oil and there is no polarity effect in synthetic ester oil in nonuniform field configuration.

It is observed that impulse withstand voltage of synthetic ester is higher than for the natural ester under both the polarities. Considering the chemical structure of both the types of esters, ester group is a common factor between the natural ester and the synthetic ester. Natural esters have several carbon double bonds (C=C) in their structure whereas synthetic ester has no double bond at all. All bonds in synthetic ester are saturated. The C=C double bonds in natural ester are rich in pi electrons which could contribute to additional streamer propagation. Also the saturated bonds has higher bond energy as compared to C=C which leads to higher impulse withstand/breakdown strength of synthetic ester as compared to natural ester.

D. *Velocity of Streamers in Insulating Oils*

A breakdown phenomena in oil is a result of streamer initiation and propagation [11].The stopping length and propagation velocity are two commonly used parameters to characterize a streamer in insulating oil. Below the breakdown voltage under specified electrode configurations, the streamer will initiate, propagate and finally will end at a certain distance less than or at gap distance. The streamer initiation mainly depends upon the radius of the electrode tip. The breakdown process is majorly dominated by streamer initiation for uniform electric field configurations while breakdown for nonuniform field is governed by streamer propagation [10]. Usually, streamer velocity is statistically distributed parameter which is a function of streamer stopping length and propagating time [11-14].

In this study, velocity of streamer is calculated by ratio of gap distance between the electrode and time to breakdown (time from the beginning of the wave till the time it collapses to zero voltage in case of breakdown event). It is assumed that streamer stopping length (propagation length) is equal to gap distance between electrodes and time to breakdown is equivalent to streamer propagating time. Here, propagation length can be defined as the straight line distance from the farthest point of a streamer from needle electrode to sphere electrode. It should be emphasized that stopping length of streamer scatter in a certain range even at the same voltage level and it will be the length of gap between the electrode under test. “Fig. 4” shows the variation of streamer velocity (km/sec) with gap distance between electrodes in mineral oil, ester oil in nonuniform field under both polarity of impulse waveshape.

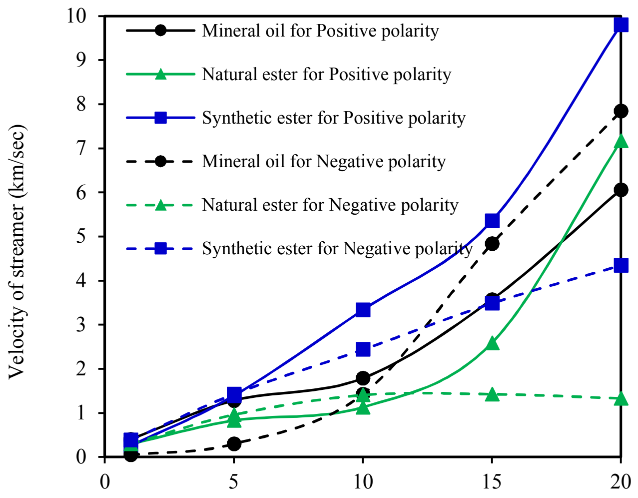

Fig.4.Streamer velocity of mineral oil and ester oil in nonuniform field configuration under positive and negative polarity of impulse

From “Fig.4” following points are observed on application of nonuniform field configuration.

- Under positive impulse, streamer velocity in synthetic ester is much higher than that of mineral oil and natural ester oil. Whereas, streamer velocity of mineral oil and natural ester oil are comparable.
- Under negative impulse, trend of streamer velocity is changing with gap distance. From 1mm to 10 mm gap distance, streamer velocity is lowest in mineral oil but after 10mm it suddenly rises and is higher than both the ester oils.

It is noted that higher streamer velocity need not mean lower withstand voltage because streamers can take different paths. Streamers do not necessarily take a direct straight-line path from one electrode to the other.

IV. APPLICATION OF ESTER OIL FOR TRANSFORMER IN DESIGN IMPLICATIONS

During insulation design analysis, impulse withstand voltage of transformer oil should always be used with a sufficient margin between withstand strength Vs maximum stress to fulfill safety requirements at the time manufacturing and processing. Hence, a reliable comparison between mineral oil and ester oil is necessary to estimate a safety margin of ester oil for optimal insulation design in ester oil transformer. Therefore, the ratios of breakdown voltage of ester oil with respect to mineral oil are calculated from experimental results under both positive and negative polarities and are shown in “Fig. 5” and “Fig. 6”.

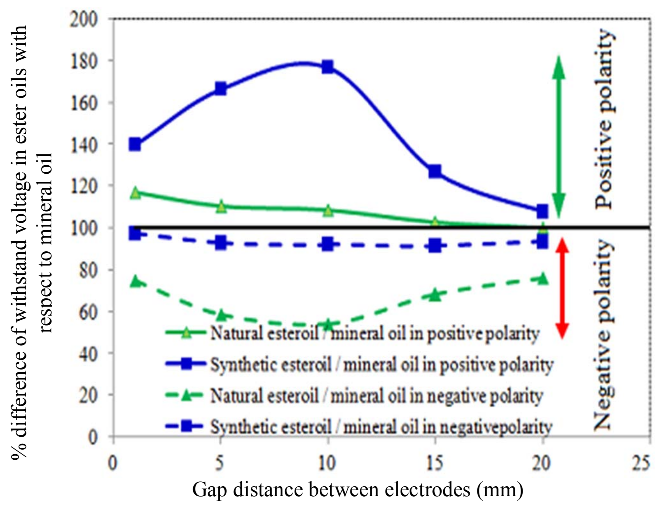

Fig. 5. Ratio of impulse withstand voltage in ester oils to mineral oil at various gap based on experimental data

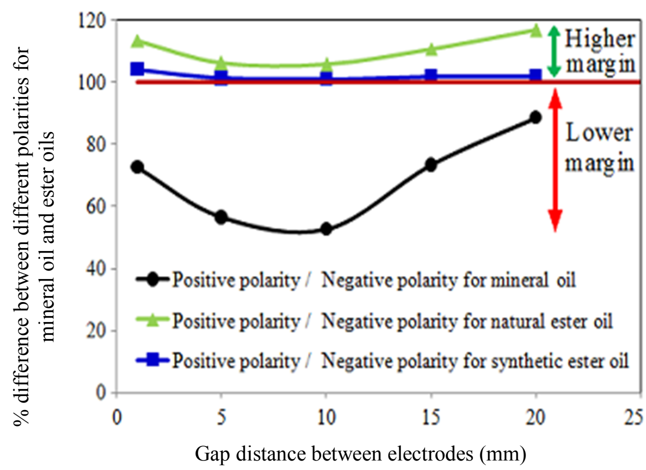

Fig. 6. Ratios of withstand voltages under both polarities of ester oils and mineral oil for various gap

From “Fig. 5”, the following inferences are observed.

- The positive impulse withstand voltage of natural ester is 20% higher than mineral oil. Moreover, this difference reduces with the increase in oil gap. Whereas negative impulse withstand voltage of natural ester is about 50-80% of mineral oil.

- Similarly, positive impulse breakdown voltage of synthetic ester oil is 10-75% higher than that of mineral oil, whereas negative impulse withstand voltage of synthetic ester is 95% of mineral oil.

Hence, under negative polarity, design guidelines of ester oil needs to be carefully adopted since withstand voltage is lower.

From the "Fig. 6" following points can be concluded.

- Difference in the withstand voltage under the application of positive and negative polarity is less for ester oil than mineral oil.
- For natural ester oil, this ratio is in range of 105-118% which signifies there is a slight polarity effect in natural ester oil. This ratio is around 100% for synthetic ester oil which means there is no polarity effect in synthetic esters.
- Polarity effect is prominently observed in mineral oil as ratio is in range of 50-90%. However, it depends upon the oil gap because up to 10mm difference between positive and negative polarity withstand voltage increases and after it decreases.

V. CONCLUSION

With increase in usage of esters as an insulating medium in a transformer, evaluation of impulse breakdown voltage of esters under both the polarities becomes important. Also, the comparison of mineral oil and ester oil is required for insulation design of a transformer under impulse excitations, since impulse testing is a routine test for above 132kV.Therefore, the objective of the paper is to determine the impulse dielectric strengths of mineral oil, natural ester and synthetic ester fluid and compare their breakdown voltages at a low failure rate (i.e. high withstand probability) under varying oil gaps with needle-sphere configuration. In addition, behavior of ester oils under positive and negative polarity is studied and compared with mineral oil.

From the experimental results, it can be concluded that, both esters behave entirely differently with respect to withstand voltages as well as the behavior under positive and negative polarities. Under positive polarity, withstand voltages of mineral oil and natural ester oil are comparable whereas withstand voltages of synthetic ester oil is the higher. This same trend is followed for velocity of streamer as well. Therefore, it indicates that higher velocity of streamer will not lead to lower breakdown or withstand voltage. Moreover, under negative polarity, withstand voltage of natural ester oil is much lower as compared to mineral oil and synthetic ester oil whereas mineral oil is having higher withstand voltage as compared to both ester oils. The studies also indicate that polarity effect is prominent in mineral oil and natural ester oil but not observed in synthetic ester oil. It signifies that transformer insulation design guidelines of natural ester oil and synthetic ester oil should be different from each other.

In general, it is concluded that impulse strengths of ester oil are not comparable to those of mineral oil at various electrode gap distances from 1mm to 20mm in a nonuniform field configurations. In addition, to re-confirm the experimental results and withstand voltages of natural ester and synthetic ester oils under negative and positive impulse polarity, similar type of natural ester and synthetic ester oils are evaluated. From the experimental results it is found that there is only 3-4% difference between the withstand voltages. As there is polarity effect in natural ester oil at nonuniform field configurations, the conclusion is based on negative polarity test is not valid for positive polarity. However in case of synthetic ester oil conclusion based on negative polarity test is valid for positive polarity.

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