Behavior of natural ester oil under negative and positive lightning impulse stress

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Abstract—**Ester oils are becoming potential alternatives for mineral oil due to their better biodegradability, higher fire point, higher moisture tolerance and continuous overloading capabilities. With the increase in its popularity, it becomes important for transformer manufacturer and utilities to understand the complete insulating properties of esters and their impact on insulation design. In this paper, behaviour of natural ester oil under different polarities of lightning impulse waveshape are analyzed with respect to mineral oil. The breakdown strength of the mineral oil is considered as an benchmark. Two types of natural esters are used to compare the lightning impulse waveshape of polarity results with mineral oil. The impulse tests are performed with vertical configuration test cell under completely divergent field using sphere-needle electrode configuration with various gaps between the electrodes. The impulse breakdown data obtained from all the impulse polarity tests are statistically analyzed by 3 parameter weibull distribution in order to establish the 1% breakdown voltages for natural ester oil and mineral oil. Furthermore, electrical stress analysis is performed based on 1% breakdown voltages resulting in calculation of utilization factor by using FEM technique.**

Keywords—Transformer, Insulating oil, Liquid dielectrics Polarity effect, Dielectrics behaviour, Impulse test

I. Introduction

Generally, the most important insulating material in transformer is liquid dielectric (oil). Insulating oil has several functions to provide an dielectric medium, cooling and acting as diagnostics tool for condition monitoring [1-5]. Traditionally, petroleum based mineral oil is used in distribution and power transformers. With its wide availability and low cost, it has been in use for transformers since the beginning of transformer industry [1-8]. However, its poor biodegradability, low flash and fire points and high toxicity to environment are the primary causes for actively looking for substitutes for mineral oil. Therefore, technology of using natural and synthetic esters as insulating liquids in transformer is becoming common recently [9-19]. The major drivers for using ester oils as alternative fluids are: biodegradability, non-toxicity, continuous overloading performance and higher fire safety (fire point < 300°C) which considerably improve their fire-safety. The high affinity of ester oils for moisture helps in enhancing the life of the paper insulation and hence that of the transformer [14,16]. In addition, the chemical compositions of natural ester oil and synthetic ester oil is dissimilar from mineral oil. Hence, it will be interesting for power industries to know the ester oil behavior and their impact on insulation design of power apparatus.

The lightning impulse breakdown voltage is one of the important parameter to characterizes the properties of the insulating oils. In this paper, the comparison of lightning performance for natural ester oil and mineral oil are estimated based on the procedure presented in ASTM D 3300-12 [15]. Time to breakdown is also measured with the help of the voltage waveform displayed in DPO (Digital Phosphorous Oscilloscope). It is the time between the beginning of the voltage waveform to the moment of sudden collapse.

Most of the insulation failures that happen in transformers are due to non-uniformity in the field experienced by insulation which leads to failure of insulation system inside the transformers [14,16-18]. Hence, sphere-needle configuration are considered in this paper to create nonuniform fields between the electrodes under impulse voltage excitations [16]. The sphere-needle configurations is considered to simulate a conditions where initiation of discharge takes place locally in the transformer [14,16]. In additions, the performance of two natural esters (2 different manufacturers) and a mineral oil is examined under lightning impulse. The impact of both positive and negative polarities is explored. The obtained breakdown voltage data of the oil is further analyzed by Weibull distribution (3-parameter) to predict the 1% failure probability breakdown voltage for each type of oil [14,20,21]. Further, from time to breakdown, velocity of streamer is calculated under both positive and negative polarity.

II. Generation of lightning impulse waveshape

Generally, transformer insulation experiences various electrical stresses at different locations during its normal operating conditions and abnormal conditions. The insulation systems of transformer has combination of oil and paper. The dielectric strength of the transformer insulation system is predominately determined by oil insulation due to lower permittivity of mineral oil. The present study focuses on behavior of the selected oils (mineral oil and natural ester oil) under impulse conditions.

A 2-stage impulse generator having the nominal rated voltage of 280 kV and energy 1.96 kJ is utilized to generate the standard lightning impulse of both polarities is used for the study [20]. Digital phosphorous oscilloscope (DPO) is used to record the waveforms with proper sampling rate. The waveforms are also registered by a digital phosphorous oscilloscope at sampling rate up to 1Gs/Sample. The Marx impulse generator circuit is shown in Figure 1.
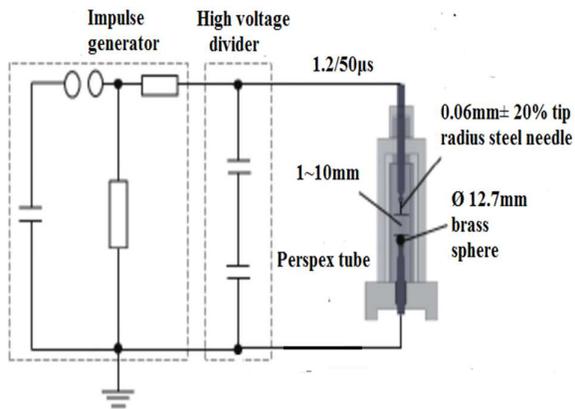
Figure 1. Schematic diagram for impulse test with sphere-needle configuration

III. EXPERIMENTAL DESCRIPTIONS

A. Insulating oils under test, test cell & electrode configuration

Insulating oil in transformer plays an important role in maintaining the efficient and reliable functioning of the power transformer [14,20]. Dielectric strength of insulating oil is determined by its physical and molecular structure. The chemical nature of insulating oil depends on the polar and non-polar component in the oil. The conventional mineral oils used in transformers predominantly consist of paraffinic, naphthenic and aromatic structures. The natural ester oils are obtained from natural vegetable seeds (such as soybean, rapeseed etc.,) consist of triglyceride fatty acid esters. A highly refined mineral oil (Transol grade), produced by Savita Oil Technologies Limited is used as the benchmark. The natural ester oil used in the paper are BioTransol manufactured by Savita Polymers Limited which is referred as natural ester oil 1 and the second natural ester oil obtained from the market [20,21]. Both natural ester oils are refined forms of soybean seed oil.

A cylindrical (vertical) test cell made up of transparent perspex made as per the standard ASTM D3300 is used to establish the breakdown voltage of natural ester oil by an experimentally confirmed and statistically supported value for various gaps between electrodes under different polarities of impulse waveshape (Figure 2). The oil holding capacity of the cell is 500ml with the dimensions of height 430mm, inner diameter 50mm and outer diameter 100mm. The dimensions are chosen to ensure that the breakdown is only restricted to the electrode gap. The sphere electrode is fixed and the point electrode is mounted on the top side. The gap distance can be varied in steps of 0.5mm using screw gauze provided as an attachment. The electrode configuration is an important parameter which decides the electric field as well as breakdown voltage of any insulating liquid [14,18-21] The point electrode is made up of steel material which can be ordinary phonograph needle with radius of curvature of 0.06mm±20% and the sphere ground electrode is made up of brass material of diameter 12.7mm. The needle electrode is changed after 5 breakdowns as drawn tip needle is not recommended. The polarity of a discharge can be determined by polarity of the needle electrode this electrode configuration.

Figure 2. Sphere-needle electrode configurations and experimental test cell

B. Sample preparations

The quality of insulating liquids plays a vital role in the studies carried out. Therefore, moisture and particle content in the oil needs to be controlled [14, 18,20,21]. The received new oil from drum are filtered by filter paper with the pore size of 0.45 μm. The filtered mineral oil and ester oil are then degassed and dehydrated at 90-100°C for 2 hours under vacuum at 500 mmHg to remove moisture content. After dehydrating the entire oil, sample is kept for 24 hour to cool down at atmospheric temperature under vacuum before conducting the lightning impulse test under different polarities [20]. Karl Fisher titration equipment is utilized to measure the moisture content present in the oil sample. The relative humidity of the oil is regularly checked during the experimental studies. Table I shows the properties of the oil samples used for impulse testing.

TABLE I. PROPERTIES OF OIL SAMPLES BEFORE IMPULSE TEST

Properties	Mineral oil	Natural ester oil 1	Natural ester oil 2
Breakdown voltage in kV for 2.5mm gap	65-70	70-80	70-80
Water contents in PPM	4-5	50-55	50-55
Relative saturation in %	10	7	7

C. Testing procedure

Generally, various testing methods including rising-voltage, up-and-down and multiple-level have been used for impulse breakdown tests. Selection of the method does not influence the comparison of trends between oil types under impulse breakdown voltage conditions [14,16,20]. In this study, multiple level methods are adopted in order to create stress on the oil. The multiple level method is utilized as per ASTM D3300 standard procedure [15]. Total 10 breakdown voltages test are performed for each oil sample. The experimental procedure is as follows:

Step 1: The initial voltage level is 60% of expected breakdown voltage.

Step 2: Impulse voltage is increased in steps of 2 kV for both positive polarity and negative polarity.

Step 3: At each voltage level, three shots are applied and the time interval between two consecutive shots is 60 seconds.

Step 4: After breakdown occurred, at least 5 minutes time interval is allowed before the next shot.

Step 5: Between two consecutive tests there is at least 20 minutes time interval.

Step 6: Oil sample is regularly changed after about 10 breakdowns on average in order to get consistent results.

IV. EXPERIMENTAL RESULTS

A. Weibull distribution analysis

To statistically analyse the breakdown voltage, Weibull distribution is the best suited function than a normal distribution and Gumbel distribution to fit the breakdown voltage data and to estimate the breakdown voltages at various breakdown probability based on interest [14,16,20,21]. It estimates the combination of statistical parameters (specific shape, scale and threshold), which fit the breakdown data with different failure probability values. In this context, application of 3-parameter Weibull distribution gives a better choice for engineers to indicate at which level of low probability (1% or less) the designed insulation structure will breakdown [14,16] with knowing the values of specific shape, scale and threshold. Hence, in this paper, three parameter Weibull distribution plots of the breakdown results are obtained according to least square method under various gaps and polarities. For example, Figure 3 show Weibull distribution plots of breakdown voltage data of mineral oil and natural ester oil for the gap of 10mm under negative polarity of the impulse wave shapes. Table II shows the withstand voltage of mineral oil and natural ester oil using Weibull distributions under negative polarities.

From the Figure 3, 99% withstand voltage of mineral oil under negative polarity is 150.36 kV. As the predicted results always have unavoidable uncertainty, it can be obtained by considering the 95% confidence interval. From the Figure 3, it can be seen that actual values of withstand of mineral oil that is predicated by 95% confidence interval might not be same for both the positive and negative polarity but it will be somewhat around of their respective values. With 95% confidence interval, it is 95% probability that the actual withstand value of negative polarity it will be between 148.77 kV to 153.43 kV. Similar predication can be made for natural ester and it is shown in Table II.

It is observed that withstand voltage mineral oil is higher in negative polarity as compare to natural ester whereas in positive polarity both are comparable. For the insulation

designing it is more reliable to use lower limit of confidence interval rather than using the predicated withstand voltage.

TABLE II. EVALUATION OF WITHSTAND VOLTAGES USING WEIBULL DISTRIBUTION OF NEGATIVE POLARITY WITH 10mm OIL GAP

	Mineral oil	Natural ester oil 1	Natural ester oil 2
1% failure probability (kV)	150.36	81.60	82.46
95% Confidence interval (kV)	148.77 - 153.43	78.53 - 82.82	79.30 - 83.64

B. Estimation of breakdown or withstand voltage during impulse test

During insulation design of transformer, the withstand voltage of insulating oil should be provide the sufficient limits to ensure the safety margin. Therefore, designer will design the insulation on basis of 1% probability breakdown voltage or 99% withstand voltage [14]. The insulating oil of in-service transformer experiences gradual decrease of withstands voltage due to ageing process. Therefore, insulating oil with higher withstand voltage ensures better and safe operation of transformer.

Results under negative and positive polarity impulse test for electrode gaps 1mm, 5mm and 10 mm are shown in Table III and IV respectively that includes average breakdown voltage, standard deviation and median of the experimental breakdown data. From Table III & IV followings points are observed under negative polarity, mean breakdown voltage of mineral oil is higher as compared to natural ester oil. This difference is gradually increased with respect to electrode gap.

- Under positive polarity, mean breakdown voltage of mineral oil is lower as compared to natural ester oil.

- In case of negative polarity, standard deviation for mineral oil and natural ester oils are comparable. However, under positive polarity, the standard deviation of mineral oil is higher than natural ester oil. The standard deviation is increased for higher gap for all insulating oil under both the polarities.

- The mean breakdown voltage and standard deviations of both natural ester oils are comparable. The difference in breakdown voltage between both the natural esters is around 1 to 2kV, which can be ignored.
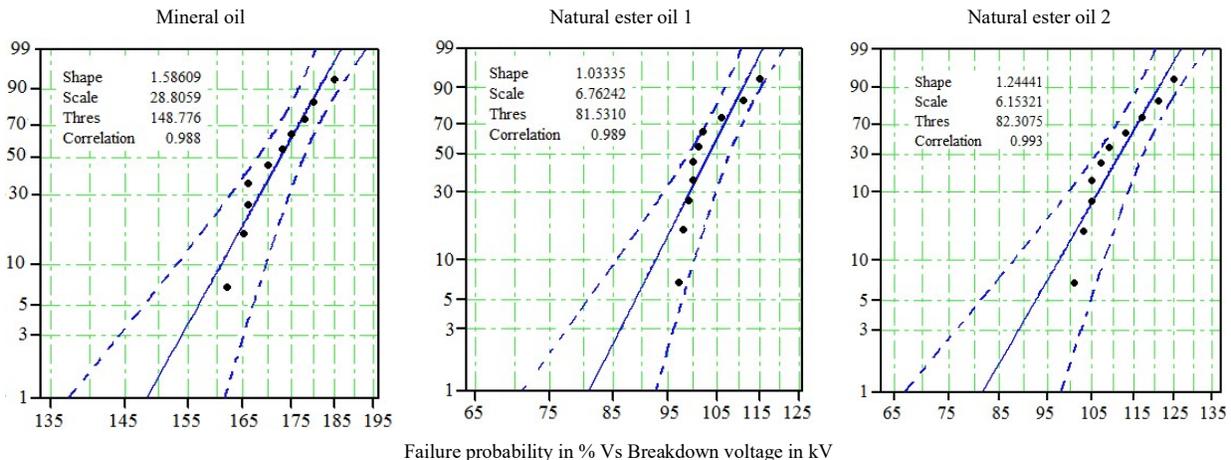

Figure 3: Weibull distribution of different insulating oil under negative polarity under sphere-needle configurations with 10mm gap

- In mineral oil, positive polarity breakdown voltage is much lower as compared to negative polarity breakdown voltage.

In natural ester oil, positive polarity breakdown voltage is slightly higher as compared to negative polarity breakdown voltage. High electron affinity of ester molecules is the main reason of lower breakdown voltage in negative polarity. Due to this property, esters facilitate easier propagation of negative streamers and hence show lower withstand voltage.

TABLE III. MEAN BREAKDOWN VOLTAGE, STANDARD DEVIATION AND MEDIAN OF DIFFERENT INSULATING OIL UNDER NEGATIVE POLARITY

Type of liquid	Electrode gap (mm)	Average value (kV)	Standard deviation (kV)	Median (kV)
Mineral oil	1	36.8	2.5	36.5
	5	97.7	4.4	97
	10	173.6	5.9	169.9
Natural ester oil 1	1	35.2	2.3	36
	5	63.2	4.6	63.5
	10	82.3	5.7	83.5
Natural ester oil 2	1	34.7	2.6	35.7
	5	62.6	4.7	61.9
	10	81.9	5.6	82.5

TABLE IV. MEAN BREAKDOWN VOLTAGE, STANDARD DEVIATION AND MEDIAN OF DIFFERENT INSULATING OIL UNDER POSITIVE POLARITY

Type of liquid	Electrode gap (mm)	Average value (kV)	Standard deviation (kV)	Median (kV)
Mineral oil	1	35.3	3.8	36
	5	65.8	4.7	65.5
	10	81.7	6.8	81
Natural ester oil 1	1	42.8	2.2	42.4
	5	72.7	3.2	73
	10	89.1	5.0	90
Natural ester oil 2	1	43.3	2.1	43
	5	73.5	3.4	73.6
	10	88.3	5.2	89.7

From the Figures 4 and 5, the following points are observed due to impulse application:

- Under negative polarity, 1% breakdown voltage of mineral oil is higher as compared to natural esters (Figure 4). It is also observed that with increase in gap, percentage difference between mineral oil and natural ester is drastically increased like for 10mm mineral oil is almost 50% higher than that of natural ester. This may be due to high electron affinity of ester molecules that makes them weaker in the presence of negative polarity.
- Under positive polarity, natural esters are superior as they are having higher 1% breakdown voltage as that of mineral oil (Figure 5). Mineral oil is around 4-5% lower in terms of breakdown voltage as compared to natural esters.

  In addition, both the natural esters are having almost same values of 1% breakdown voltage under both the polarities. A difference between both is of 1-2% which

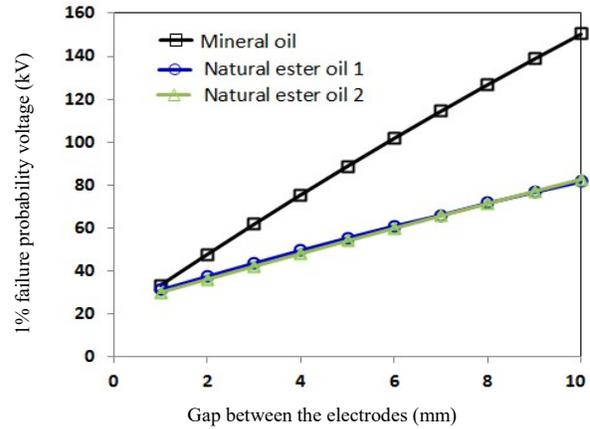can be ignored due to oil handling at the time of testing and processing.

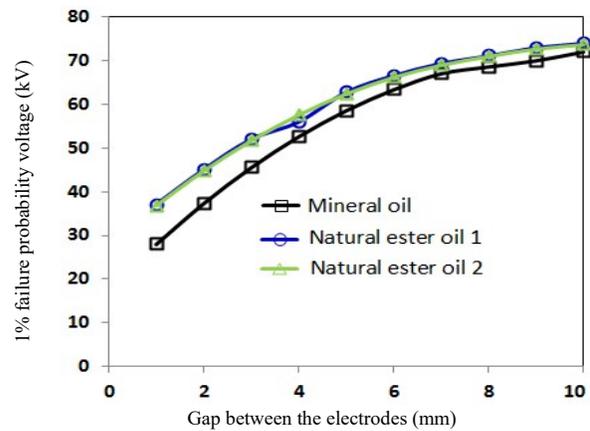Figure 4. Comparison of different insulating oil under negative polarity

Figure 5. Comparison of different insulating oil under positive polarity

C. Streamer velocity

Generally, streamer velocity depends on time to breakdown. Streamer velocity is calculated by dividing the gap distance and time to breakdown which is recorded by the oscilloscope [14,16]. Figure 6 and 7 shows the graph between velocity of streamers and gap distance between the electrodes for negative and positive polarity respectively considering all the three testing liquids. The following observations are made from Figures 6 & Figure 7.

- Under negative polarity shown in Figure 6, the streamer velocity in mineral oil is very and it is ranges between 0.05-0.32 km/sec as that of both the natural esters. In natural ester oil 1, streamer velocity range is around 0.3-1.08 km/sec whereas in natural ester oil 2 ranges between 0.31-1.11km/sec. Hence, streamer velocity of both the natural ester oil are comparable.
- Under positive polarity shown in Figure 7, the streamer velocity of natural esters is low. For natural ester oil, streamer velocity range is between 0.34-1.18 km/sec and for natural ester oil 2 ranges between is 0.3-1.18km/sec whereas for mineral oil is approximately 0.4-1.5 km/sec.
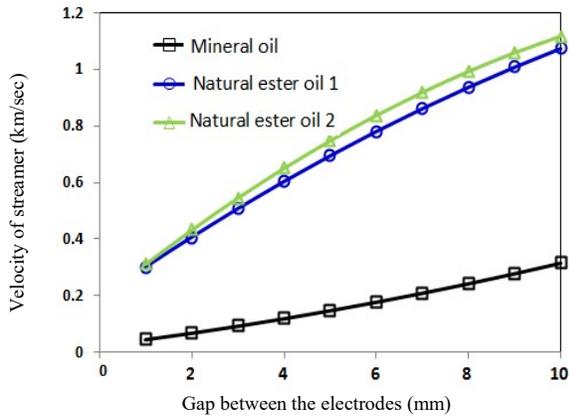
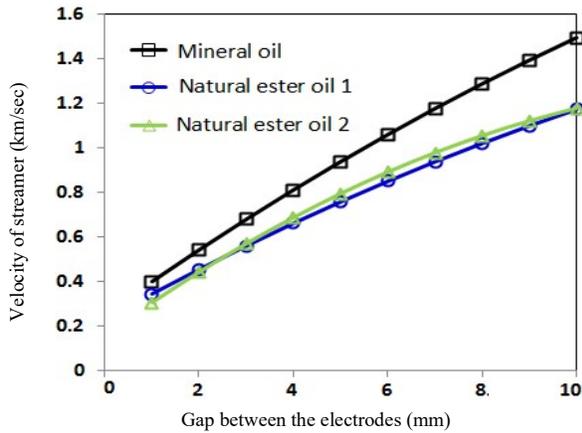Figure 6. Velocity of streamer in different insulating oil under negative polarity.

Figure 7. Velocity of streamer in different insulating oil under positive polarity.

D. Degree of uniformity

Behavior of oil when subjected to electric stress is important parameter for insulation design. The performance of the oil dielectric strongly depends upon the field configurations and magnitude and its durations of applied voltage etc., In additions, there is no comprehensive physical theory of the breakdown of insulating oil. Generally, the distribution of electrical stress between the insulating materials during impulse test depends on the permittivity of the insulating materials. The higher value of permittivity for natural ester oil is close to solid insulation improving the electric field distribution along the transformer insulating materials [14]. It is not only essential to know the existing maximum field intensity, but also the maximum permissible electric stress with electric field distribution for the dielectric in use. A perfect integration of these two may provide a reliable, economical, and durable insulation system for transformer to utilize the ester oil.

Breakdown mechanism is mainly related to the uniformity of electrical field in the geometry of electrode configurations. The utilization factor is commonly utilized to find the degree of uniformity. The higher the utilization factor, higher the degree of uniformity a field configuration. The electrical field distribution across the insulation between different electrodes is computed using FEM based software (ELECNET). From the field plots, utilization factor is calculated to analyse the electrode geometry effects on the breakdown characteristics

of the given insulation. Two-dimensional Newton Rapson equation in electrostatic field is solved using FEM software. The distance between the electrodes is varied from 1mm to 10mm in steps of 1mm. The variation of utilization factor with respect to gaps between the electrodes under negative and positive polarity is shown in Figures 8 & Figure 9.
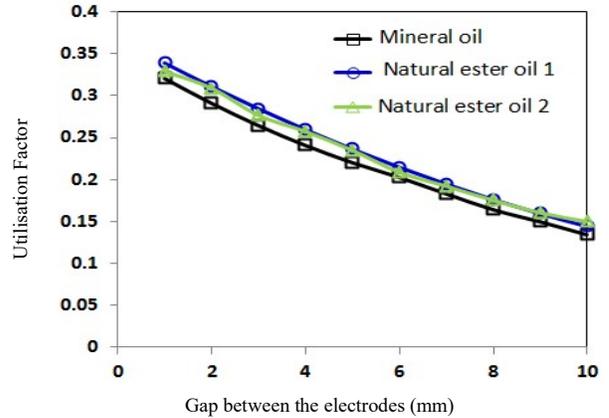

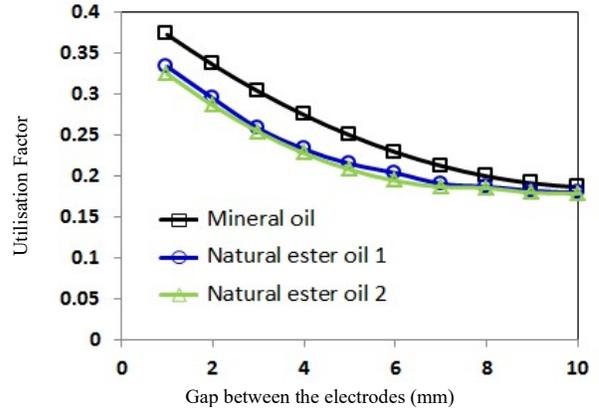Figure 8. Comparison of different insulating oil under negative polarity

Figure 9. Comparison of different insulating oil under positive polarity.

From Figures 8 and 9, the following points are observed

- Under negative polarity, utilisation factor is in the range of 0.13- 0.33 for all the insulating oils. Moreover, Mineral oil has lower utilisation factor as compared to natural ester oil, which signifies it is withstanding higher electric stress at 1% failure probability breakdown voltage.

- Under positive polarity, utilisation factor is in range of 0.17-0.37 for all the insulating oils. Moreover, natural ester oil has lower utilisation factor as compared to mineral oil, which signifies it is withstanding higher electric stress at 1% failure probability breakdown voltage.

V. CONCLUSION

With growing interests in power industries to utilize the ester oil as alternative to mineral oil for transformer, an experimental analyses is performed to predict the withstand voltage of natural ester oil with respect to mineral oil under different polarities of lightning impulse waveshape. It is found that, under negative polarity of impulse, withstand voltage of ester oils is lower as compared to mineral oil. This behavior is result of high electronegativity of ester molecules

which makes them electrically unstable under negative polarity. However, under positive polarity the withstand voltage of ester molecules is slightly higher as compared to mineral oil. It's also found that the streamer velocity of mineral oil is much higher than natural esters under negative polarity. Further, under positive polarity natural esters has more streamer velocity. In both the polarities, the utilisation factor decreases for all insulating oils as with the increase in gap distance.

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