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Research Article

Breakdown Voltage And Partial Discharge Inception And Extinction Voltage Variations In Mineral, Natural And Synthetic Ester Oils

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Abstract: The power transformer is a crucial element in power system network. The oil provides the insulation and cooling effect to transformer for high voltages and temperature rises in conductors. The dielectric breakdown voltage test is a method to determining the amount of contamination in insulating oil. Usually the contaminant is water, but it can also be conductive particles, dirt, debris, insulating particles and the by-products of oxidation and aging of the oil. In this study, breakdown voltage variation of insulation oils which is used for high voltage equipment is investigated. Three types of oils such as petroleum based mineral oil and ester based natural and synthetic ester oil are used to determine highest breakdown strength as per IEC60156 standard. Also partial discharge experiments are carried out by modeling transformer insulation as pigtail specimen and impregnated in different oils individually and their inception and extinction voltage are determined to find their PD withstanding strength. From the experimental results it is found that ester based oil shows higher breakdown and partial discharge inception and extinction voltage compared to traditional petroleum based mineral oil.

Key word: Mineral oil, natural ester oil, synthetic ester oil, breakdown voltage, inception and extinction voltage

1 Introduction

The reliability of the power sector mainly contributes to the economy and well-being of the country. The power sector has a significant role to play in the economic growth of any country. The ever growing demand for power imposes the highest demand quality. The generation, transmission, and distribution are the three systems of power sector where transformer plays a vital role. The power transformer reliability is normally high and lifetime of transformer normally exceeds 25 years. Transformers are vital elements in all the stage of electrical system and are considered very important due to the long repair time and complete system dependencies of transformer. CIGRE sponsored International survey revealed that main causes for failures of transformers are chemical faults about 1%, thermal faults accounts for 9%, dielectric faults about 31%, mechanical faults accounts for 53%, and other faults were accountable for the remaining 6% of failure [1,2].

According to IEEE Electrical Insulation is defined as "Material or a Combination of Suitable Non-Conducting Materials that Provide Electrical Isolation of Two Parts at Different Voltages"[3] solid material can be porcelain or resin also there can be more than one insulation is used such as Mineral Oil and Paper or Mineral Oil, Paper and Pressboard. Insulation is a most critical part of transformer. For safe operation of transformer sufficient insulation must be provided between different active parts of the transformer. Insulation isolate coils from one another or from the core and tank, also ensures the safety of the transformer against accidental over voltages. Insulation systems of transformer around the world mainly consist of cellulose paper based solid insulation and insulating oil.

Petroleum-based insulating fluids were the first dielectric liquids considered for high-voltage transformer; According to Harlow J, et.al.,[4] the first oil-filled electrical transformer was manufactured in 1890. The first petroleum-based fluid was based on low viscosity paraffinic oil which as good insulation capability and heat transfers routine but due to high pour point this oil cannot be used at low temperatures paraffin crudes were replaced with naphthenic-based oils, which showed lower pour point temperatures and had higher oxidation stability. The main disadvantages of petroleum-based fluids were its low fire resistance [5]. Similar to mineral oil Silicon based oil is a K class, less flammable fluid. But both mineral and silicon oils have significant negative impact on environment such as they contaminate soil and natural waterways in the case of an accidental spill, due to their poor biodegradable properties [6]. Considering ecology and safety in view, mineral oil and silicon oil no longer considered as best insulating liquids hence there is rapidly growing demands for ester based insulating liquids for transformer application [7].In recent year there are many studies to find suitable alternative to mineral oil because of many disadvantages, future scarcity and polynuclear aromatic hydrocarbon presence in mineral oil. Hence much attention given to ester based oils. Natural ester oil and synthetic ester oil have been given lot of attention as alternating insulating liquids [8].Esters oils are readily biodegradable, high moisture tolerable, less flammable K class fluids and less toxic. According to aquatic biodegradation test conducted in Germany, Natural Ester oil is considered as biodegradable substance and nonhazardous to water. According to section 450.23 of U.S. National Electrical Code, Natural Ester is defined as less flammable fluids [9].Typical Insulating properties of various liquids are listed in the table 1.3 [10].

2. PIG-TAIL SPECIMEN

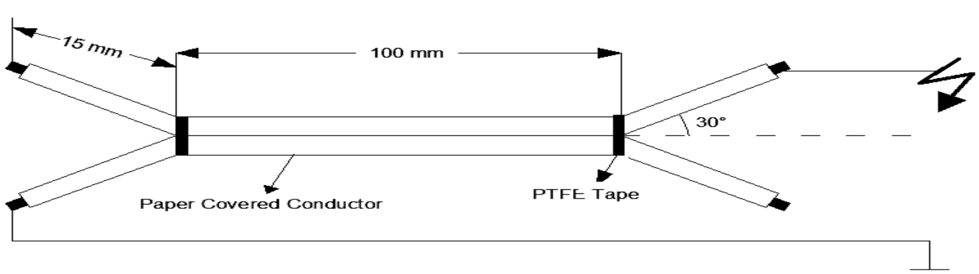

Fig. 1

The power transformer insulation winding condition is simulated in the laboratory. The pig-tail model comprising of three portions, one straight portion and two bend portions on either sides as shown in Fig.1. Straight portions have 100mm length at the center with two bent portions of 15mm on either side, making an angle of 30° with the horizontal. The two copper conductors are joined together and held firmly by the wrapping of PTFE (polytetrafluoroethylene) tape at the two ends of the straight portion. The conductors are wrapped with 3 layers of 50 micron thickness Kraft paper insulation confirming to IEC-60554-3-5 standards used for the transformers. The designed pig-tail specimen is dried to remove moisture content in specially designed oven at a temperature of 130°C for 12 Hours [11]. For further experimentation 50 such samples are prepared.

3 IMPREGNATION OF PIG-TAIL SPECIMENS

The pigtail specimens is immersed in respective oils for experimentation, total 15 samples are taken of which 5 samples each for mineral oil, natural ester oil and synthetic ester oil for impregnation purpose. Experiments are started initially with mineral oil. 2 liters of oil is poured to a borosilicate glass beaker and pigtail specimen is impregnated. The filled beaker is kept in the oven and heated at 130º C for one day and then allowed to cool down in oven itself to achieve the impregnation of oil with specimen. Similarly same procedure is repeated for natural ester oil and Synthetic ester oil with temperature of oven is set to 90º C. The impregnated pigtail specimens are then used for PD Experimentation.

4. OIL BDV TEST SETUP

The break down voltage (BDV) of particular oil is the voltage at which it breaks down when subjected to an AC electric field with a continuously rising voltage in a standard test configuration as per IEC60156 Standard [12].The BDV gives an idea about the amount of voltage needed to be carried out during the course of experiments without breakdown of the specimen. It sets the maximum voltage needed to be handled in the experiment.The study is carried out in a test cell of 750ml oil capacity. The brass spherical electrodes of diameter 25mm are mounted on a horizontal axis with 2.5 mm gap as shown in Fig. 2. The test cell is thoroughly cleaned by rinsing with the test oil. The gap between the electrodes is set to an accuracy of ± 0.01 mm by means of thickness gauge.The axes of the electrodes are immersed to a depth of approximately 40 mm before putting the oil for testing. The oil is poured slowly into the test cell to avoid the formation of air bubbles. The test voltage is applied at a rate of 2kV/s as per IEC 60156 standard. After each breakdown, the oil is gently stirred as per IEC60156 2018 revision, so as to keep away the carbon particles between the electrodes.

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Fig. 2: BDV Test setup

5. TEST CELL SETUP FOR PD

The test cell is made up of a cylindrical Borosilicate glass container with a perspex lid of 100 mm dia, 10mm thick and fitted with rubber O-ring to make the chamber leak proof. The schematic diagram of pigtail arrangement and photographs of test cell is shown in Fig.3.

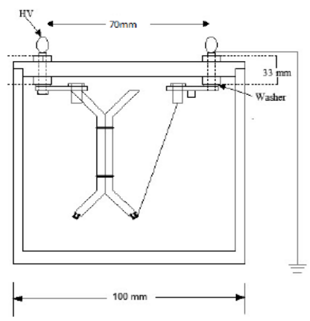

Fig.3

6 Experimental Procedures

6.1 Oil BDV Test Procedure

The test cell is filled with 750ml of mineral oil without the formation of any bubbles into a 2.5mm spaced spherical electrode arrangement test cell. The input voltage is increased at a rate of 2kV/s in accordance with IEC60156 until breakdown occurs. Experimental setup is designed with safety protective equipment to cut off power immediately after breakdown. Experiments are repeated for ten trails, by allowing waiting time of 2minutes for mineral oil between the trails as per new 2018 revision of IEC60156, which includes use of stirring system in between trails of experimentation. For ester based oil rest time allowed in between trails is 10minutes because of higher viscosity of natural and synthetic ester oils compare to mineral oil. The reading obtained is tabulated. Similarly, experiments are repeated for Natural ester oil and synthetic ester oil. Before changing oil from the test cell care has been taken to thoroughly clean with soap water and ethyl alcohol, dried in oven for one day and rinsed with the oil to be used for the breakdown voltage test. Electrodes are polished using abrasive cloth and cleaned with ethanol.

6.2 INCEPTION AND EXTINCTION VOLTAGE PROCEDURE

In order to determine the discharge inception voltage (V**inc**), as per standard IEC TR 61294:93/IS 17245:2019 [13] the applied voltage is gradually increased till the discharges begin to appear. The voltage is maintained for one minute and the value of the voltage at which discharges occur contentiously for one minute is taken as the inception voltage (Vinc). Voltage is then gradually reduced and the voltage at which the pulses just disappear is taken as the extinction voltage (V**ext**). The applied voltage is then reduced to zero and a time interval of five minutes is allowed before the measurement of next observation. Five minute waiting will allow positive and negative ions remaining after previous pd activity to recombine [14]. Depending on the consistency and repeatability of observations, about 10 observations for V**inc** and V**ext** for each sample are made.

7. EXPERIMENTAL RESULTS AND DISCUSSIONS

7.1 **The Oil Breakdown voltage (BDV)**

The Breakdown voltage (BDV) of mineral oil, natural ester oil and synthetic ester oil and Partial Discharge Inception and Extinction voltages of three layers kraft paper insulated copper conductor are discussed in this section

Table.1 Breakdown voltage value of different oils

Trail No.	Mineral oil (kV)	Natural Ester oil (kV)	Synthetic Ester oil (kV)
1.	31	74	65
2.	32	74	64
3.	32	73	63
4.	34	74	62
5.	32	73	62
6.	32	74	62
7.	32	74	62
8.	32	75	62
9.	32	74	62
10.	32	74	62
Average	**32.1**	**73.9**	**62.6**

The breakdown voltage values obtained for mineral, natural ester and synthetic ester oils under AC Voltage are tabulated as shown in Table 1. The average breakdown voltage of mineral, natural ester and synthetic ester oils are 32.1kV, 73.9kVand 62.6kV respectively and its graphical representation are shown in Fig. 4. It is observed that average breakdown voltage of natural and synthetic ester oils are higher than that of mineral oil by 130.21%and95.01%respectively**.** Also, it is observed that breakdown voltage of natural ester oil is higher than synthetic ester oil by 18.05%. It is reported in the literature as per IEC 60156 standard the BDV of mineral oil are 31kV [15],32kV [16].Breakdown voltage data available in literature for natural ester and synthetic ester oils varies depending upon the type of oils used for experimentation sourced from different manufacturers and its composition are not known to the investigators.

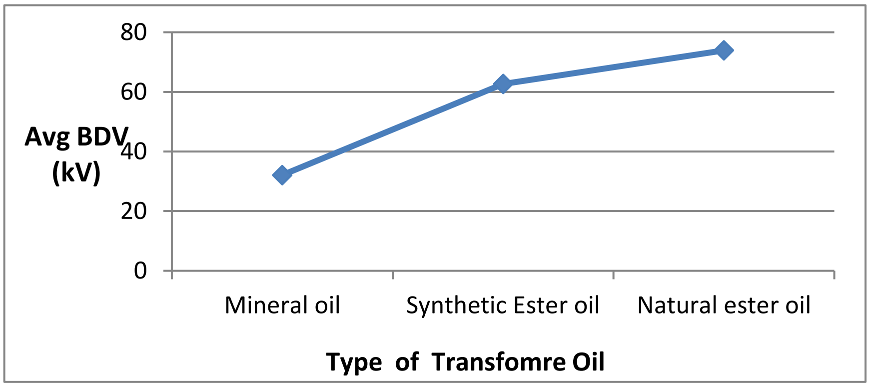

Fig.4 variation of Breakdown voltage in different oils

7.2 Inception and Extinction Voltage of Pigtail Specimens

The experimental inception and extinction voltages are shown in Table 2 for pigtail specimens impregnated in mineral oil, natural ester oil and synthetic ester oil independently. Typical variations of inception and extinction voltages are shown graphically in Fig. 5 and these trails correspond to ten trails. Inception voltage observed in mineral oil, natural ester oil and synthetic ester oil are 2.7kV, 3.2kV and 3.4kVrespectively.It is observed that the inception voltage is higher by 18.52% in natural ester and 25.93% in synthetic ester oil respectively compared to mineral oil. Also, the inception voltage of synthetic ester oil is 6.25% higher than that of natural ester oil. The increase in extinction voltage is 20% in natural ester oil and 28% in synthetic ester oil respectively compared to mineral oil. Also the extinction voltage of synthetic ester oil is 6.6% higher than that of natural ester oil.

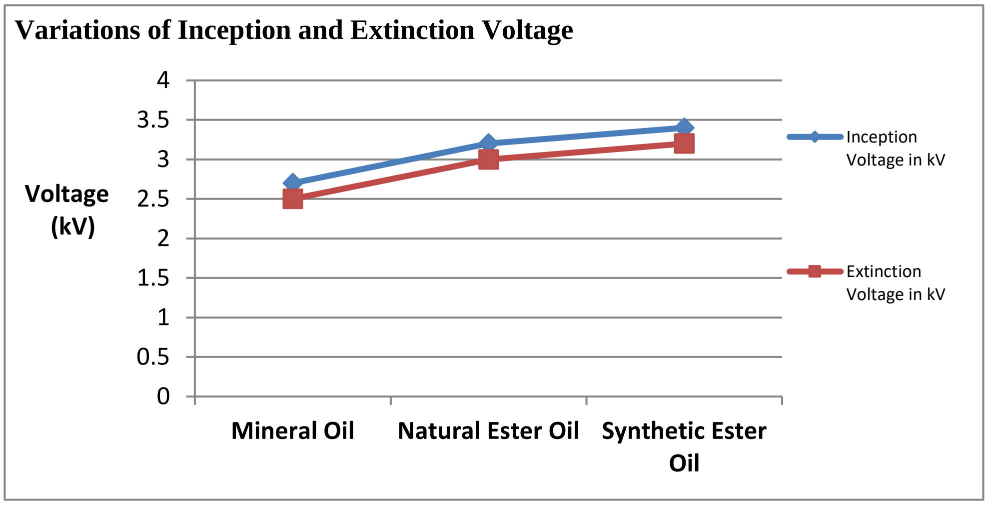

Fig.5 variation of Inception and extinction voltages in different oils

Table 2: Inception and Extinction voltages of pigtail specimen impregnated in mineral oil, natural ester oil and synthetic ester oil

Type of oil	Inception Voltage (kV)	Extinction Voltage (kV)
Mineral Oil	2.7	2.5
Natural Ester Oil	3.2	3.0
Synthetic Ester Oil	3.4	3.2

8. Conclusion:

Insulating liquid plays an important role for the life span of the transformer; petroleum-based mineral oil has become dominant insulating liquid of transformer for more than a century. But the usage of petroleum-based mineral oil, has affected the environment for its non biodegradability property. Ester oils are advantages compare to mineral oil due to low flammability, negligible environmental impact, high moisture tolerance, high flash point, high breakdown strength, higher biodegradability. It is observed that the breakdown strength of natural ester oil and synthetic ester oil is almost double compared to mineral oil and hence ester based oils can withstand high electric stress. The PD inception and extinction voltage change with different types of oils used in the present work. It is observed that ester based oils have proved to be a viable substitute for mineral oil from the point of view of partial discharge inception voltage and breakdown voltage.

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