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Enhancing the Performance of Natural High Oleic Ester based Mixed Oil Paper with Nano Insulating Liquid for High Voltage Transformer

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Abstract: ***Nowadays insulation paper for high voltage transformer is based on natural ester due to increase in bio degradability and operating life. Recently oil selection based on unsaturated fatty acid content was proposed and this shows better insulation properties compared to normal ester oil. Nowadays nanofluids have the potential to overcome conventional transformer oil by reducing acidity and oxidation process. In this work, olive oil is selected based on low poly unsaturated fatty acid content. Mineral and olive oil is mixed with definite ration and then blended with different proportion of nano particle. This oil is blended with nano particles such as Al_2O_3 and TiO_2. Insulating properties such as degree of polymerization, mass fraction, breakdown voltage, moisture content and acidity are measured as per standards. By comparing the experimental results, Al_2O_3 shows better insulating properties.***
Index Terms: ***Antiageing property, Ester oil, Insulating properties , Mineral oil, Mixed oil, Oil paper insulation nano fluid***

I. INTRODUCTION

Transformer plays a important rule in power system for reliable and efficient electrical supply. Majority of high voltage transformers are filled with oil to reduce arcing and to improve heat transfer properties [1]. Mineral oil is commonly used oil for good properties but it is on bio degradable and highly toxic. Hence researchers found natural ester oil as alternate to available liquid insulation [2,3]. Ester oil shows no toxic and biodegradable nature but acid content due to oxidation is high. Cellulose insulation is used in power transformer which is made from refined wood fibers. The main purpose of insulation paper is to reduce the short circuit forces between the winding [4]. This insulation paper impregnated in oil acts as excellent insulation with mechanical support [5].Ester oil is derived from agricultural plants and seeds. Vegetable oil consist of triglycerides namely saturated fatty acid (no unsaturated carbon bonds – palmitic and steraic acids), mono unsaturated fatty acid (one saturated fatty acid – oleic acid), poly unsaturated fatty acid (more than one unsaturated bond – linoleic and linlenic [8,10].

In recent years, lot of research work has been carried out on nano dielectrics. The result analysis shows the longer life time of insulation by providing better thermal, electrical and mechanical properties [7]. Transformer oil modified by nano conductive (Fe_3O_4) and nano nonconductive (Al_2O_3 and TiO_2.) particle shows improvement in insulation properties. Researchers show that consumption of nano fluid after a certain degree itself responsible for secondary oxidation products [5].

To overcome this drawbacks, mixed oil is proposed i.e., mixing of mineral and ester oil. For certain combination it will combine both the good properties of mineral and ester oil with low dielectric loss, low ratio of degradation, low acid number and moisture content [11].

I.Fofana et al suggested that mixture less than 20% ester content gives better heat transfer characteristics and addition of mineral oil with ester oil to insulation paper increases dielectric strength upto 10%. Performance characteristics of oil and paper depend on miscibility of blended combination [2,3]. I.L.Hosier et al analysed the procedure to select ester oil based on fatty acid content. Oil wit low poly unsaturated fatty acid content reduces viscosity and prone to oxidation. Oil with high mono unsaturated fatty acid content shows oxidation resistance. Oxidation stability is a key factor to anti-ageing property [12].

The aim of this work is to investigate the insulating mixed oil blended with different ratio of nano fluids In this work, olive oil is selected with low poly and high mono unsaturated fatty acid blended with Al_2O_3, Fe_3O_4 and TiO_2 That prepared sample is impregnated wth karamay 25# insulation paper. Insulation properties are measured separately measured for oil (viscosity, breakdown voltage, moisture content, flash point) and paper (breakdown voltage, moisture content in paper, degree of polymerization and mass fraction of paper) as per IEEE and IEC standards. Experimental results are compared to select best sample.

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II. METHODOLOGY

Naphthenic based mineral oil and high oleic olive oil is selected as base samples for investigation. High oleic means high mono and low poly unsaturated fatty acid. As per suppliers description about fatty acid content olive oil has 77% mono fatty acid and 8% poly fatty acid content.

Mixed samples are prepared by blending the mineral and olive oil in the ratio of 80:20, 500ml of oil sample is taken in beaker and placed in stirrer for one hour with 900 rpm of rotation to achieve complete miscibility of oils.

Nano fluid is prepared by dispersing certain amount of Al_2O_3, Fe_3O_4 and TiO_2 in oil sample by ultrasonicator. All the samples are prepared with different concentration and put into vacuum drying to neglect the effect of micro bubbles formedduring sonication process.

Insulation paper is prepared by dispersing insulation paper of 1mm thickness in oil sample at a temperature of 90°C for 5 hours. Various blended samples are shown in Table 1

TABLE 1 BLENDED OIL SAMPLES

S. No	Samples	Oil combination
1	MO	100% Mineral oil (MO)
2	OO	100% olive oil (OO)
3	OS1	80%MO + 20% OO
4	AS1	80%MO + 20%OO + 1 gm Al_2O_3
5	AS2	80%MO + 20%OO + 2 gm Al_2O_3
6	AS3	80%MO + 20%OO + 3 gm Al_2O_3
7	AS4	80%MO + 20%OO + 4 gm Al_2O_3
8	TS1	80%MO + 20%OO + 1 gm TiO_2
9	TS2	80%MO + 20%OO + 2 gm TiO_2
10	TS3	80%MO + 20%OO + 3 gm TiO_2
11	TS4	80%MO + 20%OO + 4 gm TiO_2
12	FS1	80%MO + 20%OO + 1 gm Fe_3O_4
13	FS2	80%MO + 20%OO + 2 gm Fe_3O_4
14	FS3	80%MO + 20%OO + 3 gm Fe_3O_4
15	FS4	80%MO + 20%OO + 4 gm Fe_3O_4

Performance of oil samples is analyzed by measuring the properties such as electrical property (breakdown voltage), physical properties (viscosity, flash point) and chemical properties (acidity, moisture content). Performance of oil paper is analysed by measuring moisture content in paper, mass fraction in paper and degree of polymerization. Properties are measured as per ASTM and IEC standards. The measurement standards, apparatus and standard values are given in Table 2.

TABLE 2 MEASUREMENT TECHNIQUES AND STANDARD VALUES OF PROPERTIES

Properties	Measurement setup	Standards	Values
Breakdown voltage (kV)	Breakdown voltage kit	IEC 60156	30
Viscosity at 40°C (cSt)	Redwood viscometer	ASTM D-445	50
Flash point (°C)	Pensky Martin closed cup nethod	ASTM D-92	180
Acdidty (mgKOH/g)	Titration with KOH	ASTM D-974	0.04
Moisture content (ppm)	Karl Fischer titration	IEC 60814	35
Degree of polymerisation	UV spectrophotometer	ASTM D5837	1200

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III. EXPERIMENTAL DESCRIPTION

The measurement procedure and analysis on the properties such as electrical property, physical properties and chemical properties of base oil samples and mixed oil samples with nano fluid is described in below sections. All the measurements are conducted at room temperature and atmospheric pressure conditions.

A. Properties of Insulating Oil

Viscosity of oil is the indication of resistance to flow at normal condition which influence in heat transfer characteristics of oil [3]. As per standard ASTM D-445, viscosity is measured using redwood viscosmeter [20].

Flash point is the lowest temperature at which it produces a temporary flammable mixture in air when the external cause of fire is introduced [4]. As per ASTM D-92, flash point is measured using pensky martin closed cup method [21].

Breakdown voltage is measured using sphere gap arrangement with gap spacing 2.5mm. Breakdown voltage is the maximum instant voltage at which the insulating medium starts conducting. Breakdown voltage depends on oil purity, environmental condition and electrode configuration [11]. As per IEC 60156, breakdown voltage is measured using breakdown voltage kit [19].

Acidity accelerates the oxidation process in oil. It causes rusting of iron in transformer windings. Ester oilwith high mono and low poly shows low acid content. Acidity is a measure of both oxidation stability and gassing tendency [14]. Acidity of oil is measured by titration with KOH. It is expressed in mg of KOH required to neutralize the acid present in a gram of oil. As per ASTM D-974, acidity is measured using titration with KOH [22].

Moisture content in oil is measured using Karl Fischer titration method carried out by titration with methanol and iodine, presence of 0.1% of water will reduce 20% dielectric strength [12]. As per IEC 60814, moisture content is measured using karl fischer titration method [23].

Insulating properties of base oil samples are measured and shown in Table 3

TABLE 3 PROPERTIES OF BASE OIL SAMPLES

Samples	Viscosity (cSt)	Flash point (ºC)	Breakdown voltage (kV)	Moisture content (ppm)	Acidity (mgKOH /g)
MO	18.34	178	32	7.28	0.00724
OO	98.34	278	43.6	12.92	0.0157
OS1	28.30	198	35.84	8.30	0.0089

From this experimental results. Mixing of mineral and olive oil shows increase in flash point, breakdown voltage compared to mineral oil and reduction in viscosity, acidity and moisture content compared to olive oil. Mixing of oil with higher proportion of olive oil will increase viscosity, acidity and moisture content hence 80:20 blending ratio is selected and OS1 is selected as base sample for further investigation

B. Water Absorption Fundamentals of Insulation Paper

1) Moisture content assessment is often derived from karl fischer titration method in laboratory although it is recognized that it cannot reveal the moisture content in insulation paper if the oil temperature is unstable [12]. Hence this theoretical method is used to calculate moisture in insulation paper by substituting the moisture content in oil [6]. Equation (i) shows water concentration in new paper.

Water concentration in new paper [17] is given by

$$C = 2.173 \times 10^{-7} \times P_v(T)^{0.6685} \times e^{\frac{4725.6}{T}} \qquad (1)$$

Where C is the water concentration in paper expressed as a fraction of the weight of the dry paper, T is the absolute temperature, $P_v(T)$ is the vapour pressure of water expressed in atmospheres.

Water activity is calculated by using the equation (2),

Water activity at temperature T

$$a_w(T) = \frac{P_v(T)}{P_o(T)} \qquad (2)$$

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$P_o(T)$ is the partial pressure of water above pure water in equilibrium

$$P_o(T) = 0.00603 \times e^{\frac{17.502 \times T}{240.97+T}} \quad (3)$$

Equation (2) can be rewritten as

$$P_v(T) = 0.00603 \times e^{\frac{17.502 \times T}{240.97+T}} \times a_w(T) \quad (4)$$

The water activity of oil may be expressed mathematically as

$$a_w = \frac{w}{s} \quad (5)$$

w is the water concentration in oil
s is the solubility of water in oil at same temperature

$$s = 10^{A-\frac{B}{T}} \quad (6)$$

A and B are empirical coefficients that depend on type of oil A=17.42 B=1170 for 1mm insulation paper.

1. Mass fraction is the ratio of one substance with mass to the mass of total mixture [18]. Mass fraction ofmoisture concentration in paper and oil was calculated with equation (7) and (8)

$$W_{paper} = \frac{C_{paper}}{C_{paper} + C_{oil} \times \frac{M_{oil}}{M_{paper}}} \times 100\% \quad (7)$$

C_{paper} and C_{oil} are the moisture content of insulation paper and oil, W_{paper} and W_{oil} are the mass fraction of moisture in oil and paper.

$\frac{M_{oil}}{M_{paper}}$ = mass fraction of oil to paper is 20 for 1mm paper.

2. Degree of polymerization refers to the number of basic units of cellulose, which is an effective indicator of ageing degree. Degradation of paper is analyzed using degree of polymerization [24]. The rate of paper degradation is directly proportional to the temperature. So insulation paper will usually degrade faster at the top of the transformer than at the bottom [6]. Degree of polymerization is measured using UV spectrophotometer. Peak intensity value is measured from spectrophotometer and substituted in equation (8).

$$DP = \frac{\log(0.88 \times c) - 4.51}{-0.0035} \quad (8)$$

C is the peak intensity value measured from UV spectrometer.

TABLE 4
PROPERTIES OF BASE OIL PAPER SAMPLES

Samples	Moisture content in paper (%)	Mass fraction in paper (%)	Degree of polymerization
MO	5	84	1100
OO	19	92	1184
OS1	10.8	91	1185

IV. RESULT

A. Experimental Results of Nano based Oil

Breakdown voltage, acidity and moisture content are measured as per IEC standards. Experimental results of different combinations

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ofnano based oil is shown in Table 5

TABLE 5 EXPERIMENTAL RESULTS OF NANO BASED OIL

Samples	Breakdown voltage (kV)	Acidity (mgKOH/g)	Moisture content (ppm)
AS1	46	0.00847	10.45
AS2	54	0.00842	11.56
AS3	68	0.00815	11.05
AS4	74	0.00791	10.74
TS1	41	0.00902	11.49
TS2	44	0.00831	12.45
TS3	53	0.00819	14.61
TS4	59	0.00803	12.51
FS1	43	0.00893	13.14
FS2	48	0.00841	12.56
FS3	61	0.00817	11.17
FS4	69	0.00793	11.09

B.Experimental Results of Nano based Blended Oil Paper

Moisture content in paper, mass fraction in paper and degree of polymerisation are measured as per IEC standards. Experimental results of different combinations of nano based oil paper is shown in Table 5

TABLE 5 EXPERIMENTAL RESULTS OF NANO BASED OIL PAPER

Samples	Moisture content in paper (%)	Mass fraction in paper (%)	Degree of polymerization
AS1	10.2	89	1189
AS2	9.5	85	1191
AS3	8.6	83	1198
AS4	8.4	81	1204
TS1	10.9	93	1182
TS2	10.3	90	1187
TS3	9.7	88	1189

Samples	Moisture content in paper (%)	Mass fraction in paper (%)	Degree of polymerization
TS4	9.5	87	1192
FS1	14	95	1177
FS2	13.6	93	1179
FS3	12.1	90	1182
FS4	10.4	89	1184

Performance of oil samples is analysed by measuring chemical (moisture content in paper and mass fraction in paper) and mechanical (degree of polymerization) properties based on international standards.

V. DISCUSSION AND ANALYSIS

Performance of oil sample is analysed by measuring the electrical (breakdown voltage) and chemical (acidity and moisture content)

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properties as per international standards.

A. Breakdown Voltage

Breakdown voltage is an important testing procedure for oil. During the transformer operation for a period, insulating oils become degradation which results in loosing cooling capacity of oil [2]. Fig. 1. shows the breakdown voltage for different combinations of nanoparticle.

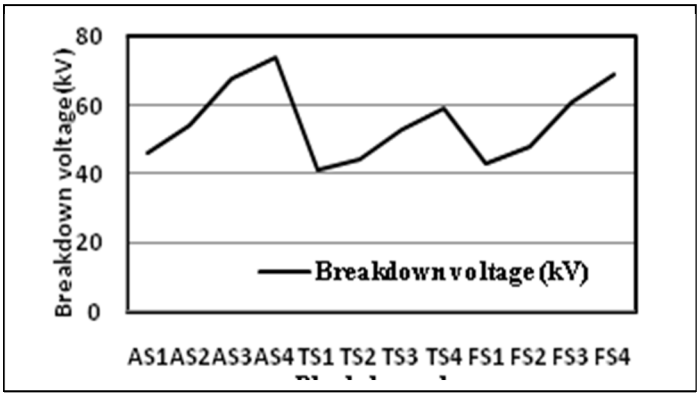


Fig.1. Breakdown voltage for different samples

From this experimental result, it is evident that AS4 shows higher breakdown voltage and TS1shows lower breakdown voltage. Al_2O_3, and based sample shows higher breakdown voltage than Fe_3O_4 and TiO_2. TiO_2 based blended oil shows lower breakdown voltage than other two samples. By comparing the above results, with the increasing proportion of nano particle will increase breakdown voltage. AS4 shows high breakdown voltage with 74kV among the other blended samples.

B. Acidity

Acidity measurement is very important to analyse the degradation rate of both and insulation paper. High acid count in oil will cause primary oxidation process. Hence oil should be selected at minimum acid number [3]. Fig.2. Shows acidity value for different combinations of nanoparticle.

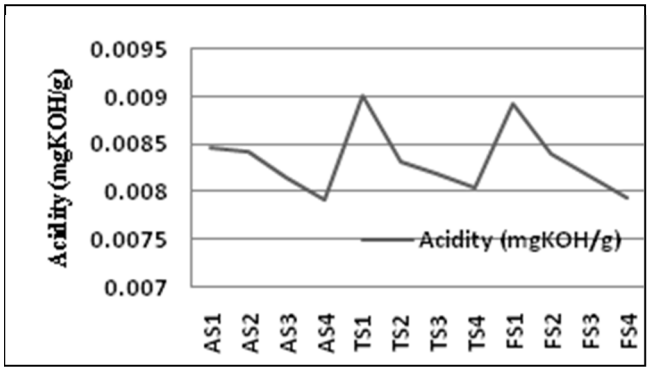


Fig.2. Acidity for different samples

From the experimental results, it is known that AS4 shows lower acid content and TS1 shows higher acid content than other samples. By comparing the above results, increase in nano particle count will reduce the acidity content in oil. AS4 shows lower acidity content of 0.0079mgKOH/g.

B. Moisture Content in Oil

Moisture content in will increase due to oxidation and hydrophilic property. This moisture content will increase short circuit forces between the windings. It also reduces the breakdown voltage in oil and insulation paper. Hence oil should have lower moisture

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content [18]. Fig.3. shows moisture content value for different samples.

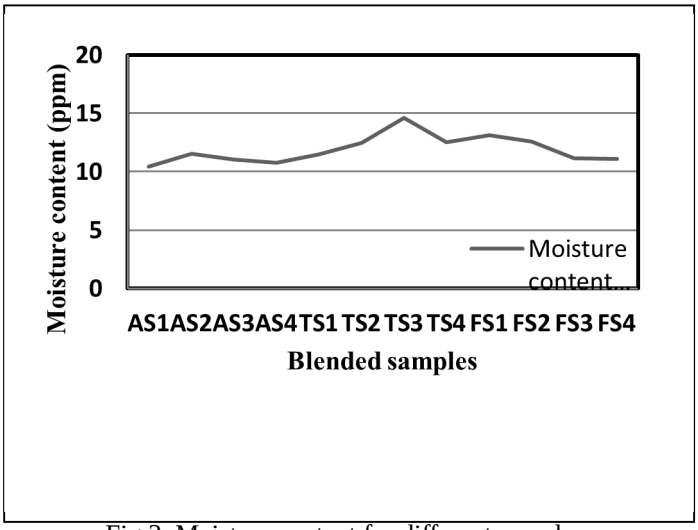
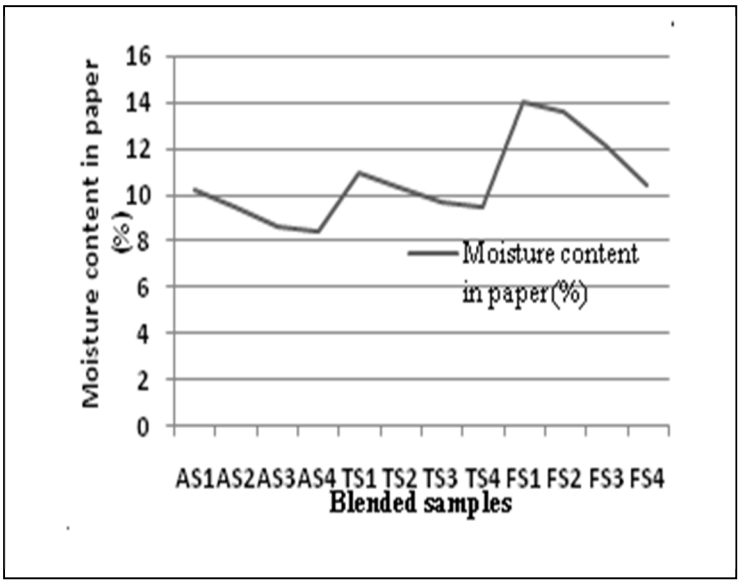


Fig.3. Moisture content for different samples

The measurement of water content reveals that the AS4 shows lower moisture content and TS3 shows higher moisture content. By comparing the above results increase in nano particle count will partially reduce the moisture content because it is purely depends on chemical composition of oil. AS4 shows lower moisture content with 10.74 ppm.

C. Moisture Content in Insulation Paper

Moisture content of solid insulation is a persistent concern for a power transformer as it causes several detrimental effects on the insulation's integrity [6]. Hence insulation paper should have lower moisture content. Fig.4. shows moisture in paper for different samples.



From the experimental results, it is known that AS4 shows lower moisture content and FS1 shows high moisture content. By comparing the above results, it is evident that moisture content in insulation paper decreases with increase in nano particle amount. AS4 shows lower content by 8.4% than other samples.

1)Mass Fraction in Oil and Paper: Mass fraction is used to calculate the mass of oil and paper. Best sample should have low mass fraction for easy reconstruction of high voltage apparatus [18].Fig.5. shows mass fraction value for different combinations of nanoparticle.

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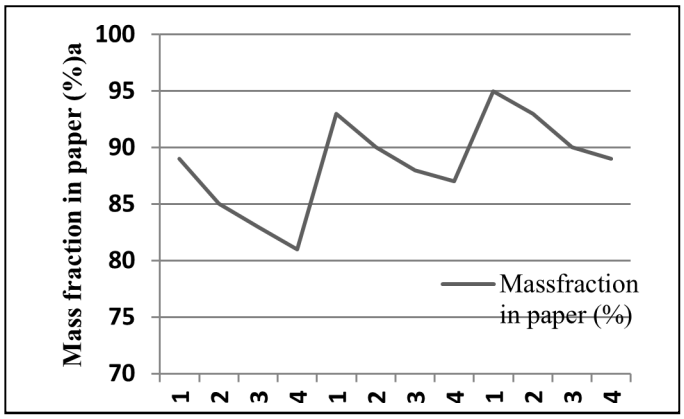
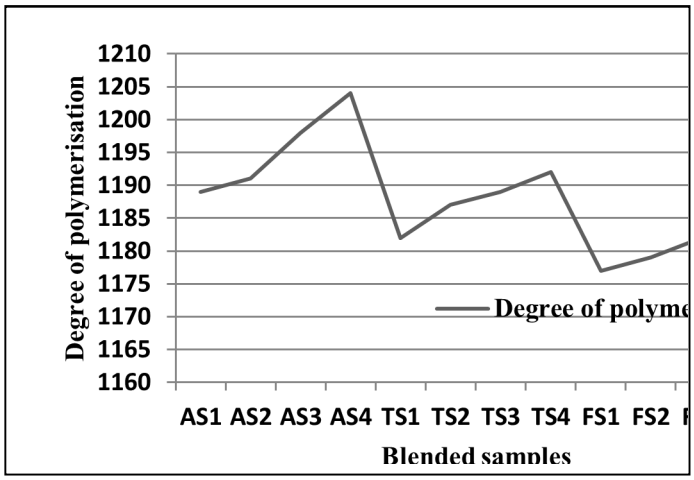


Fig.5. Mass fraction in paper

From the experimental results, it is shown that AS4 shows lower mass fraction and FS1 shows higher mass fraction than other samples. By comparing the above results, it is evident that mass fraction will decrease with increase in nano particle count. AS4 shows lower mass faction by 81% than other samples.

2) *Degree of Polymerization:* Degree of polymerization depends on moisture, oxygen content and acidity of oil. New insulating paper should have typically 1200 DP. This ensures the high tensile strength of insulation paper [6, 18]. Hence new insulation paper should have high degree of polymerization value. Fig.6. shows degree of polymerization for different combinations of nanoparticle.



From the experimental results, it is shown that AS4 has higher degree of polymerization and FS1 shows lower degree of polymerization. It is evident from the results that increase in nano particle count will increase degree of polymerization value. AS4 shows high degree of polymerization of 1204.

VI. CONCLUSION

In this paper, three different types of nanoparticles were selected and blended with oil samples. The experimental results reveal that

A. Al_2O_3has better insulating properties in all oil and insulating properties with higher breakdown voltage and degree of polymerization and low acidity, moisture content in oil and paper, mass fraction in paper.

B. Mixed oil shows the intermittent property between mineral and ester oil with both advantages.

C. The change in properties mainly varies in oil and nanoparticle combination.

D. Based on the application area and desired characteristics, the investigated nano sample has the prospective to be an alternative to mineral oil. Only limitation is the cost of nanoparticle.

E. From the above experimental results it is evident that it will increase the lifetime of high voltage apparatus irrespective of cost.

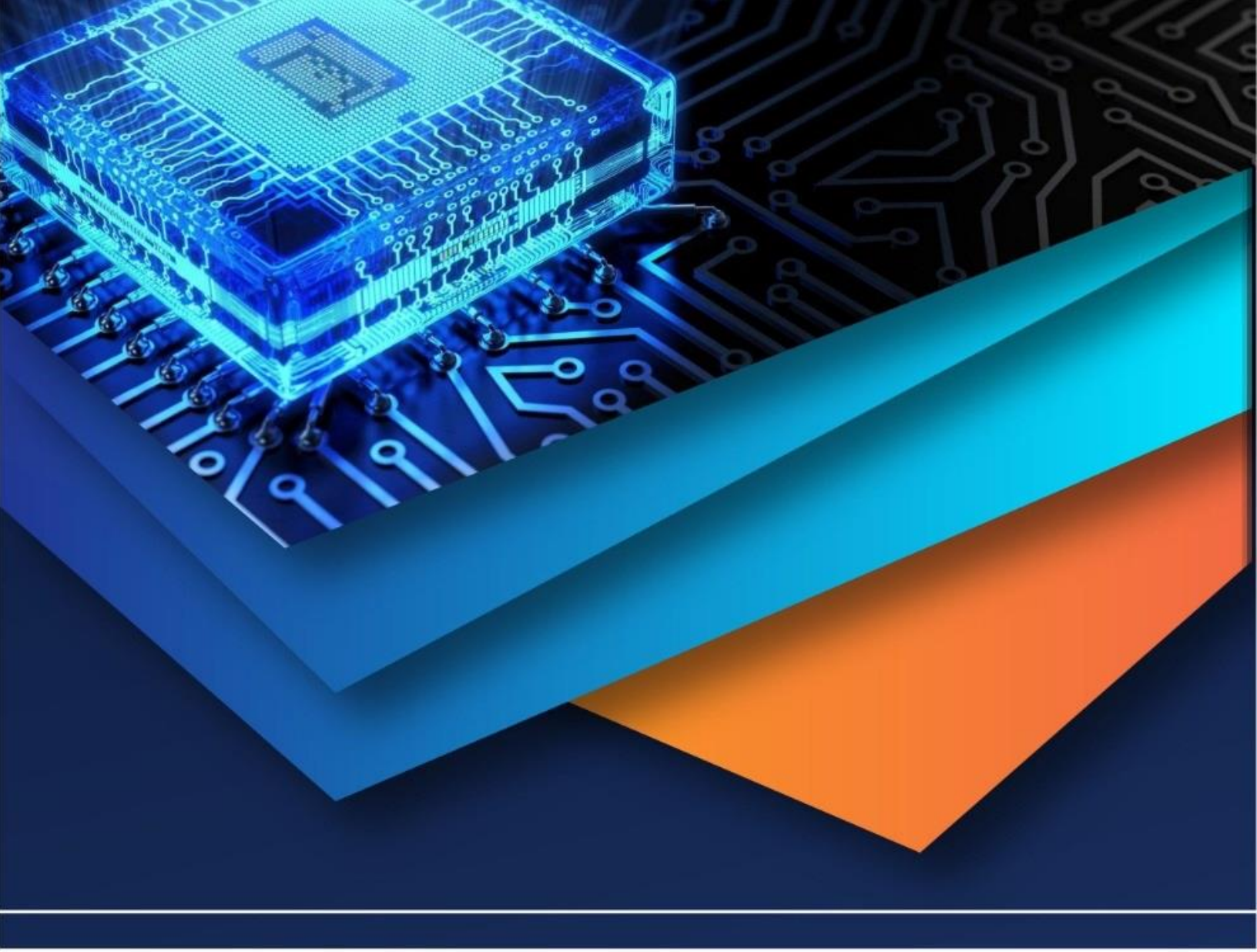
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