

Received:

31 July 2018

Revised:

1 December 2018

Accepted:

21 January 2019

Cite as: Jilani Rouabeh, Lotfi M'barki, Amor Hammami, Ibrahim Jallouli, Ameni Driss. Studies of different types of insulating oils and their mixtures as an alternative to mineral oil for cooling power transformers. *Heliyon* 5 (2019) e01159. doi: [10.1016/j.heliyon.2019.e01159](https://doi.org/10.1016/j.heliyon.2019.e01159)



Studies of different types of insulating oils and their mixtures as an alternative to mineral oil for cooling power transformers

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Abstract

Because of their availability and low cost, mineral oils have been widely used for a long time in power transformers to allow their insulation and cooling. However, their low fire safety and low biodegradability potential have made it necessary to look for other insulating liquids as an alternative to this mineral oil used in high voltage electrical equipment. This work presents an experimental study to compare between the physicochemical characteristics of mineral oil, olive oil, sunflower oil and different oil mixtures. In order to determine mainly the breakdown voltage and the electrical field intensity of electro-convection, oils insulating should be mixed in precise amounts. All tests have been realized in accordance with the standard test procedures: IEC 60156, IEC 60245 and IEC 61125. The obtained results of testing new as well as aged oil samples

concerning the resistivity, the dissipation factor $\text{tg}\delta$, the conductivity, the viscosity, the breakdown voltage, the increase of the water content and the flexibility of the oil to the movement in an electrical field, show that a half mixture of naphthenic oil and olive oil could be a potential liquid for the insulation of electrical devices and especially power transformers mounted in areas which have a non-cold climate.

Keywords: Electrical engineering, Energy

1. Introduction

For decades and precisely with the beginning of energy evolution, insulating liquids have been used for the insulation and cooling of electrical devices such as transformers, cables, switches and capacitors. Naphthenic mineral oil has long been the most preferred insulating liquid for power transformer insulation because it has a good pouring point at low temperatures, good thermal cooling capacity, low cost, high efficiency and availability on the transformers market [1, 2, 3, 7]. Despite the previously cited advantages, the disadvantages of naphthenic mineral oil, such as its high fire risk and low biodegradability potential in addition to its scarcity in the future because the oil resources will run out, have made it necessary to look for another ecological insulating liquid which has a high solubility in water and an excellent biodegradability [4, 13]. In order to find an alternative insulating liquid to the mineral oil used for the insulation and cooling of transformers, many studies have been carried out by several university research centers and by the manufacturers and users of power transformers [5, 6, 7, 16]. These studies deal mainly with the physicochemical properties of natural esters as ecological and low-flammable esters [8, 21]. The study of the physicochemical properties of natural esters and their comparison with those of mineral oils is therefore still held nowadays by several laboratories in the world. Different natural esters and their mixtures with mineral oil have already been tested and compared with the mineral oil in bath conditions new and aged [9, 10, 17]. Among the researches, some discovered that natural esters such as olive, sunflower oil compared with naphthenic mineral oil have higher inflammation and lightning marks [11]. These results show that these esters are applicable and adaptable to voltage transformers [12, 16, 17]. The main purpose of our study is to participate in the search for an insulating liquid based on natural ester as an alternative to the mineral oil of power transformers mounted in the countries of the Mediterranean basin where the climate is hot as Tunisia, Algeria, Morocco...

The purpose of our work is to study the electrical characteristics of different insulating oils and different types of mineral oil mixtures with natural esters. In the first part of this document, we mainly present a comparison of the change in the breakdown voltage values of these mixtures in terms of the ageing time. The second part is devoted to the presentation of the results obtained during the study of the

physicochemical characteristics of these insulating liquids such as: viscosity, dissipation factor, water content, resistivity...

2. Methodology

2.1. The measurement method

In this work, we used the measurement method developed to analyze the oil flexibility to the movement in an electrical field, which can lead to the appearance of a turbulent movement inside the real transformers. The study of the breakdown phenomenon of insulating oils used for the insulation and cooling of power transformers and their flexibility while moving in an electrical field requires a very sensitive measuring device. To investigate the oil flexibility while moving in an electrical field and to measure its breakdown voltage, it is necessary to use a device which diagram is presented below Fig. 1.

The use of this cell to study the breakdown voltage of insulating oil is very effective, given the advantages it has:

- Possibility of easily changing the type of electrodes suitable for the desired studies (sphere-tip for the study of the phenomenon of electro-convection and sphere-sphere for the measurement of the breakdown voltage);
- Possibility to change the field of vision in a wide range of dimensions;

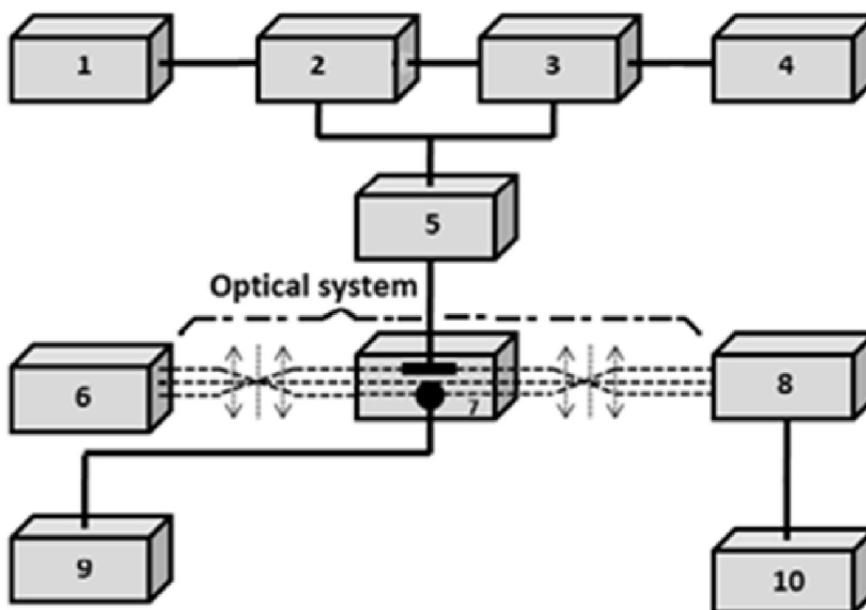


Fig. 1. Diagram of the study device of electro-hydrodynamic characteristics of insulating oils.

- Possibility of live control of the movement of oil on T.V. monitor or to take photos directly from it or to record it by video;
- Great clarity when observing the movement of the oil.

2.2. Experimental technique

2.2.1. Breakdown voltage

The breakdown voltage measurement is carried out in accordance with IEC 60156 standards [21]. Each tested sample of oil is poured into a container (spark gap) in which are placed horizontally two semi-elliptical and 36 mm diameter steel electrodes and at a distance of 2.5 mm from each other. We apply a voltage at the terminals of the electrodes and it is increased step by step at a speed of 2 kV/s until the appearance of electric shock [18]. The Eq. (1) of the voltage value in which this electrical discharge appears is the value of the breakdown voltage of the tested oil sample. Each measurement of this breakdown voltage is repeated six times. The value of the breakdown voltage adapted in this work is the average value of the six measurements of this voltage:

$$U = \sum_{m=1}^6 \frac{U_m}{6} \quad (1)$$

With: U – Average breakdown voltage, U_m – Measured voltage, m – Number of repeated measures equal to 6.

In order to dissipate the gases that occur during the electrical discharge, 10-minute breaks between each measurement are respected. Note that each time, before measuring the breakdown voltage of the next oil sample, we clean and dry the test cell and the electrodes which must be clean so as not to include craters due to the previous measurement. Due to the importance of the breakdown voltage for the determination of the oil quality which ensures the good cooling and the good insulation of the power transformers, the most suitable choice for the oil mixture, which will be studied later, will depend on the value of this voltage, taking into account its low cost and eco-friendliness.

2.2.2. Phenomenon of electro-convection in transformers insulating oils

The phenomenon of electro-convection in insulating oil is the latter's flexibility in movement in an electrical field. The obtained measurements of the initiator voltage (U_{in}) causing the appearance of the movement of oil in a model of metal electrodes: sphere - plate. The electrodes are separated from each other by $d = 8$ mm. The radius of the spherical electrode which is very interesting for the calculation of electrical

field intensity of electro-convection initiation (E_{in}) is $r = 5,5$ mm. The voltage applied to the electrodes is a DC voltage which negative polarity is related to the spherical electrode. The value of the voltage for to observe an oil movement from one electrode to another is adopted as the value of the electro-convective initiator voltage. The determination of the electrical field intensity E_{in} is expressed by the Eqs. (2), (3), (4), (5), and (6), based on the results of the measurements of the electro-convection initiation voltage.

$$E_{in} = \left[\frac{U_{in}}{d} \right] \cdot \beta \quad (2)$$

$$\beta = \frac{1}{\eta^2} \quad (3)$$

$$\eta = \frac{2p \cdot \ln p}{p^2 - 1} \quad (4)$$

$$p = q + \sqrt{q - 1} \quad (5)$$

$$q = \frac{d + r}{r} \quad (6)$$

d- Distance between the electrodes, r - Radius of the spherical electrode, η - Dynamic viscosity of the liquid.

2.2.3. Water content

The presence of water content (Eq. (7)) in the transformer oils negatively influences the dielectric characteristics of this insulating liquid and also the insulating solid (paper) [20]. The solubility of water in oil depends essentially on three factors: the temperature, the type of oil (mineral or vegetable), and its condition (new or aged). It varies according to its molecular structure and temperature and has for expression.

$$W_s = W_{oil} \cdot e^{-B/T} \quad (7)$$

W_s : Solubility of water in oil in ppm;

T : Temperature in K;

W_{oil} and B : Constants which depend on the type of oil.

In the following tests, the measurement of the existing water content in each oil sample is carried out according to the Karl Fischer method [19].

2.2.4. Dielectric loss factor $\text{tg}\delta$

For transformer oils, the dielectric dissipation factor $\text{tg}\delta$ is directly related to its conductivity and inversely proportional to the product of its static permittivity and the frequency adopted. The $\text{tg}\delta$ of Eq. (8) measurements were carried out thanks to a bridge assembly [10]. The expression of the $\text{tg}\delta$ can be shown as follows.

$$\text{tg}\delta = \frac{\sigma}{2\pi f \epsilon s} \quad (8)$$

σ : Conductivity;

ϵs : Static permittivity;

f : Frequency.

The determination of $\text{tg}\delta$ is carried out according to CEI 60247 standard based on AC capacity measurements using Sheering bridge [13].

2.2.5. Physical and thermal properties

In transformers, oil is used as insulation and cooling medium. To obtain good insulation, the value of the resistivity of the oil must be high. The purpose of measuring the resistivity of an insulating liquid is to study the ability of this liquid to oppose the electric power. In this work, measurements are performed in accordance with IEC 60247 [13].

For the insulating liquids commonly used for cooling transformers, the conductivity σ (s/m) of these liquids is generally due to the presence of ions. The variation of the conductivity of the oil in terms of the mobility of the ions is expressed as following:

$$\sigma = e(\mu^+ + \mu^-) \quad (9)$$

With:

e : Charge of the electron;

μ^+ and μ^- : Ion concentration.

The conductivity of the oil is inversely proportional to the power density and is given by the expression.

$$\sigma = \frac{E}{j} \quad (10)$$

E: Electrical field;

j: Power density.

In general, the viscosity measurements of the insulating oils are intended to study the flexibility of these liquids in the flow. Low viscosity of the transformer oil is an advantage for heat dissipation. Measurements of the viscosity of the oils studied are carried out using a viscometer and expressed in square meters per second (m^2/s) or in centistokes (cSt).

2.3. Types of oils to study

2.3.1. New oils

In comparison with paraffinic mineral oil, naphthenic mineral oil oxidizes easily but in the form of soluble sludge. Some characteristics of the different types of oils to be studied are presented in [Table 1](#).

In a cold climate paraffin-based oil has the defect of freezing quickly and consequently prevents the good operation of transformers. For this reason, naphthenic mineral oil is chosen for our study. Concerning the choice of natural esters to study, the best two types of vegetable oils mainly because of their availability in Tunisia are olive oil and sunflower oil. In what follows we adopt: MO - Mineral oil, OO - Olive oil and SO - Sunflower oil.

2.3.2. Oil mixtures

Each time the mixture of naphthenic mineral oil with one of the already selected vegetable oils are carried out with well-determined percentages. The mixtures of oils samples are carried out using a magnetic stirrer for an hour and at a rotation speed of 900 rpm. The percentages of the mixtures of naphthenic oil, olive oil and naphthenic oil with sunflower oil are presented in [Table 2](#). In this work, we adopt Oi and Si respectively as indications for the two groups of mixtures (Oi composed by

Table 1. Characteristic of different types of oils.

Types of oil characteristics	mineral oil (MO)	Sunflower oil (SO)	Olive oil (OO)
Breakdown voltage (kV)	32	43	46,5
Dissipation factor $Tg\delta$	$14 \cdot 10^{-4}$	$65 \cdot 10^{-4}$	$11 \cdot 10^{-4}$
Resistivity at 40 °C (TΩ/cm)	5,7	3	3,1
Viscosity at 40° cSt	9,3	34,5	110,3
Humidity (ppm)	90	550	200
Conductivity at 40 °C (S/m)	$175 \cdot 10^{-3}$	$333 \cdot 10^{-3}$	$322 \cdot 10^{-3}$
Electrical regency (kV/mm)	128	172	175,5

Table 2. Define the percentages of the oil mixtures.

O _i	O _i %	O _i	O _i %
O ₁	80%MO+20%OO	S ₁	80%MO+20% SO
O ₂	70%MO+30%OO	S ₂	70%MO+30% SO
O ₃	60%MO+40%OO	S ₃	60%MO+40% SO
O ₄	50%MO+50%OO	S ₄	50%MO+50% SO
O ₅	40%MO+60%OO	S ₅	40%MO+60% SO
O ₆	30%MO+70%OO	S ₆	30%MO+70% SO

the mixture of mineral oil and olive oil. S_i composed by the mixture of mineral oil and sunflower oil). The i (i = 1 to 6) represents an index of the oil mixtures and O_i% represents the percentages of the oil mixtures.

2.3.3. Aged oils and their ageing methods

The presence of water content and oxygen in the insulating oils at high temperature causes its oxidation, which leads to its ageing and consequently to the degradation of the characteristics of this liquid [7, 11]. The influence of the degree of the insulating oil ageing on the phenomenon of initiation and development of electro convection and especially on the variation of the breakdown voltage of the insulating liquid attracts the attention of several researchers [2, 7, 9, 11, 15].

To study the ageing of insulating oils (mineral oil and vegetable oil), there are four different types of ageing:

- Ageing of the samples alone;
- Ageing in the presence of insulating paper;
- Ageing in the presence of copper;
- Ageing in the presence of copper and insulating paper.

In our work, we chose the fourth type of ageing. Our choice fell on this type of ageing because it takes into consideration the main factors responsible for the ageing of oil in a transformer (oxygen, humidity and temperature). In addition it allows to accelerate the process of oxidation of oils and to obtain a more severe ageing. The volume of copper used as a catalyst is calculated so that it is proportional to the volume of the oil sample to be studied. The copper catalyst is chosen in accordance with IEC 61125 [14]. The approximate proportion used in the transformer are respected, oil 60%, copper 30% and insulating cellulose paper 10% [15]. The oils samples are subjected to ageing in stainless steel containers at a temperature of 90 °C and with a total weight of 1000 g.

3. Results and discussions

3.1. Breakdown voltage

The measurement of the breakdown voltage of the insulating oils used for the insulation and cooling of the transformers is an essential factor to evaluate the dielectric strength of these oils. The good interaction of most vegetable oils due to breakdown is related to the fact that these oils have a better affinity for water than naphthenic mineral oil, allowing them to have a low sensitivity to water content. In this work, the measurement of this voltage for different oil types and oil mixtures before and after their ageing is carried out.

The percentage of the mixtures which therefore leads to a good breakdown voltage, in addition to the appropriate cost of this insulating liquid, will therefore make it the best choice for our study of these dielectric properties.

3.1.1. New insulating oils and their mixtures

In Fig. 2, there is a presentation of the breakdown voltages of the three types of oil: one mineral oil and the two other vegetable oils as well as the breakdown voltages for the same percentages of the mineral oil with the olive oil mixtures and mineral oil with sunflower oil mixtures.

It is obvious that the breakdown voltages of olive oil and sunflower oil are respectively about 45% and 34% higher than the breakdown voltage of mineral oil. For both mixtures, the percentage decrease in the amount of mineral oil and its replacement with the same percentage of one of the natural esters leads to the increase of the breakdown voltage of the mixtures. According to Fig. 2, it is also worth noting that the mixture of mineral oil with vegetable oil (olive oil and sunflower oil) reduces the breakdown of the studied samples approximately between 10 and 35%. At point

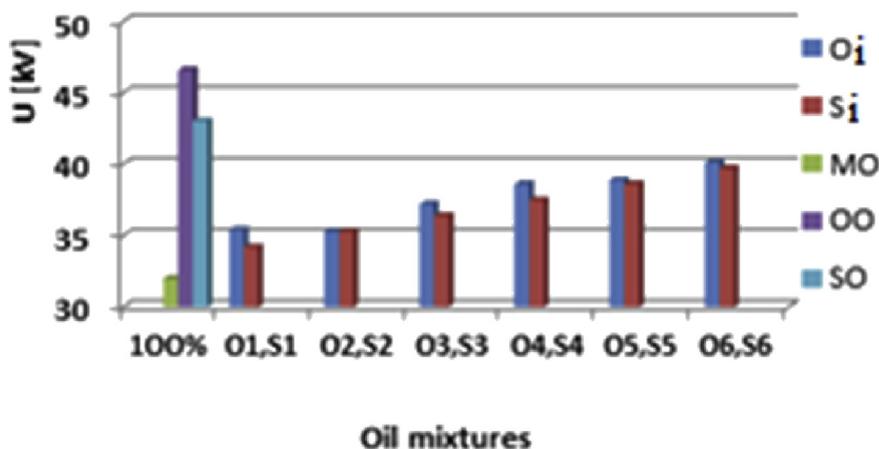


Fig. 2. Comparison of the breakdown voltage of different insulating liquids.

5 (O4 and S4) of Fig. 3, the measured values of the breakdown voltages are respectively represented 38.6 kV and 37.5 kV of the two mixtures O4 = 50% MO + 50% OO and S4 = 50% MO + 50% SO. These percentage proportions will therefore be taken into consideration for the study of the dielectric properties of these mixtures because their acceptable breakdown voltage value in addition to their low cost and eco-friendliness.

3.1.2. Aged oils

The measurement of the breakdown voltage of insulating oils, in terms of the time of their ageing, is a significant greatness to evaluate the degradation of these liquids used for the isolation of transformers.

We observe in Fig. 3, that the breakdown voltage decreases with increasing ageing time. We note that during the first 20 days of ageing, the decrease in breakdown voltage values for the different insulating liquids tested is quite low. After 30 days of ageing and arriving at the 70th day, the measured values of the breakdown voltage for the different types of vegetable oils (OO and SO) and especially the mineral oil, decreases rapidly. On the contrary and during the same period of ageing, there is a small decrease in the breakdown voltage for the oil mixtures O4 and S4 and a more remarkable decrease for the mineral oil MO. We note that during the first days of ageing, the breakdown voltages of each of the natural esters OO and SO are higher than those observed for their mixtures O4 and S4. These results are the opposite during the last days of ageing.

Through the measurements made and presented in Fig. 3, there is a clear correlation between the breakdown voltage and the ageing time of the different tested insulating

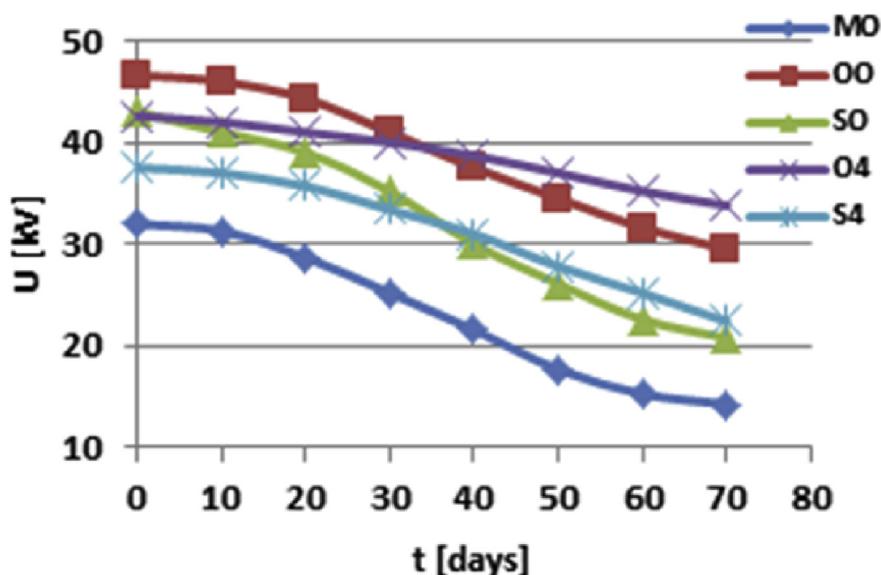


Fig. 3. Evolution of the breakdown voltage in terms of the ageing time of different insulating liquids.

liquids. One of the main factors responsible for ageing of an oil is water content, for this reason it is very interesting to study the relationship between them.

The Karl Fischer method allowed us to measure the amount of water in each sample of aged oil. Although the increase in water content is due to increasing ageing time, aged sample of oil mixture O4 has the lowest water content compared to OO and SO. From both Figs. 3 and 4, the output is a close correlation between the breakdown voltage of insulating oil and the amount of water it contains. Thus, it is clear that the growth of the water content with the ageing time of the insulating liquid follows a law similar to the growth of the breakdown voltage in terms of ageing time. According to this Fig. 4, it is remarkable that the ageing time leads to an increase of the water quantity in the insulating liquid and allows the decrease of its breakdown voltage.

3.2. Electrical field intensity of electro-convection initiation

The results of the studies carried out on aged samples of naphthenic mineral oil and oil mixtures (O4 and S4), obtained for a negative polarity, are presented in Fig. 5. The intensity values of the electrical field of electro-convection initiation measured, for different types of oil samples vary according to ageing time. The figure also shows that the mixture O4 has always the highest electro-convection initiation of electrical field intensity values during the ageing cycle followed respectively by the mixture S4 and the naphthenic oil.

The physical interpretation of these results is not easy. During the ageing time of the oil, different chemical compounds are formed, which depend on the initial physico-chemical composition of the oil. At the 10th day of ageing, the values of the

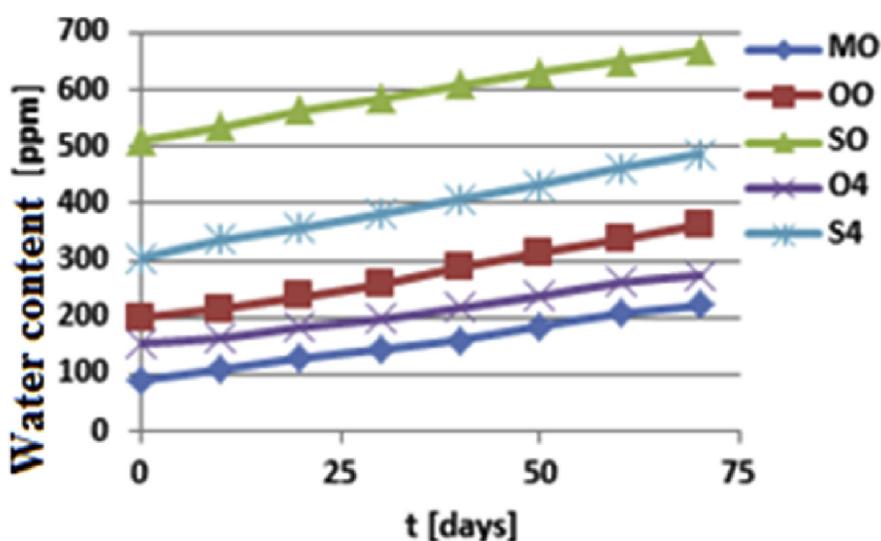


Fig. 4. Evolution of the water content in terms of the ageing time of the different insulating liquids.

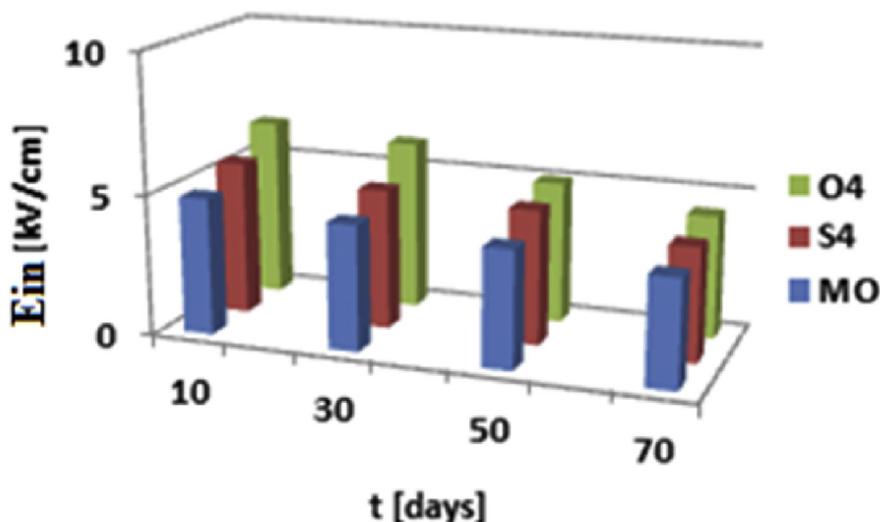


Fig. 5. Electrical field Intensity of electro-convection initiation for different aged oil samples.

intensities of the field, for the different oil samples are higher than that found at the 70th day of ageing. The explanation of this phenomenon is that at the beginning of the ageing cycle, the oil is a little dry and with increasing ageing time, the amount of water content increases gradually. The formation of water and acid can have a particular effect on the electro-chemical processes at the electrode/oil interface, playing a fundamental role in the mechanism of ion injection and electro-convection in insulating oils.

The comparison of the flexibility of these insulating liquids in motion in an electrical field is shown in Fig. 6. The application of a 2.5 kV DC voltage on the electrodes immersed in the O4 causes its movement. For the same voltage value, we perform

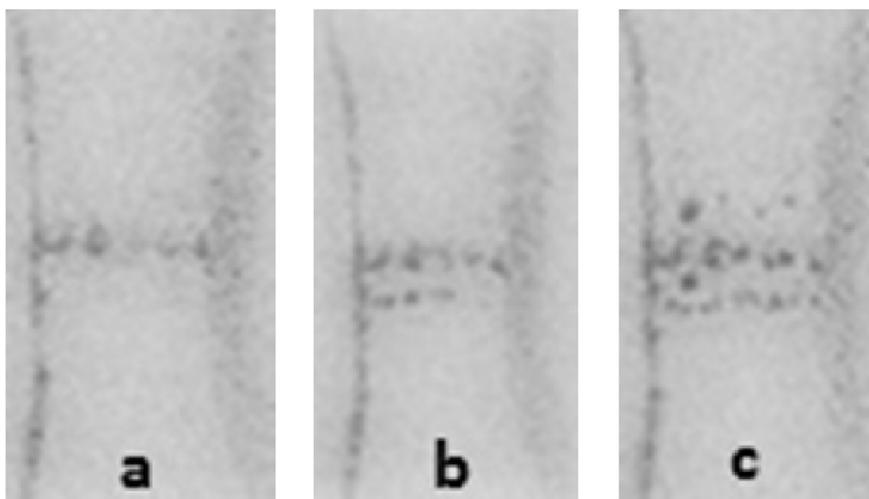


Fig. 6. Electro-convection phenomenon of for various insulating liquids; a: O4, b: S4 and c: MO.

the same test with the S4 and MO liquids (Figs. 6b and c). We notice that the movement becomes a little stronger in these last liquids in comparison with the movement observed in the O4 (Fig. 6a). The result is that MO is more flexible while moving in an electrical field respectively followed by S4 and O4 and that this flexibility in the presence of an intense electrical field can lead to a turbulent movement in the transformer.

3.3. Dissipation factor $\text{tg}\delta$

According to Fig. 7, it is noticed that the dissipation factor $\text{tg}\delta$ also increases with the rise of temperature and depends on the type of insulating liquid. The figure proves that the $\text{tg}\delta$ increases progressively with increase in the temperature according to the oil types MO, O4, OO, S4 and SO. Generally good insulating oils should have a low $\text{tg}\delta$. According to this hypothesis, as soon as the temperature exceeds 60 °C, the good results are observed for the oil MO followed by O4 and OO whereas the liquids S4 and SO are classified respectively the last in comparison with the tested insulating liquids with a remarkable growth in terms of temperature.

3.4. Resistivity

The influence of temperature on the resistivity of the insulating oils is very important. The results presented in Fig. 8, show that the increase in temperature is accompanied by a remarkable decrease in the resistivity of the different types of tested liquids. According to Fig. 8, the best resistivity is observed for the mineral oil followed by the two mixtures O4 and S4 which have almost the same resistivity values

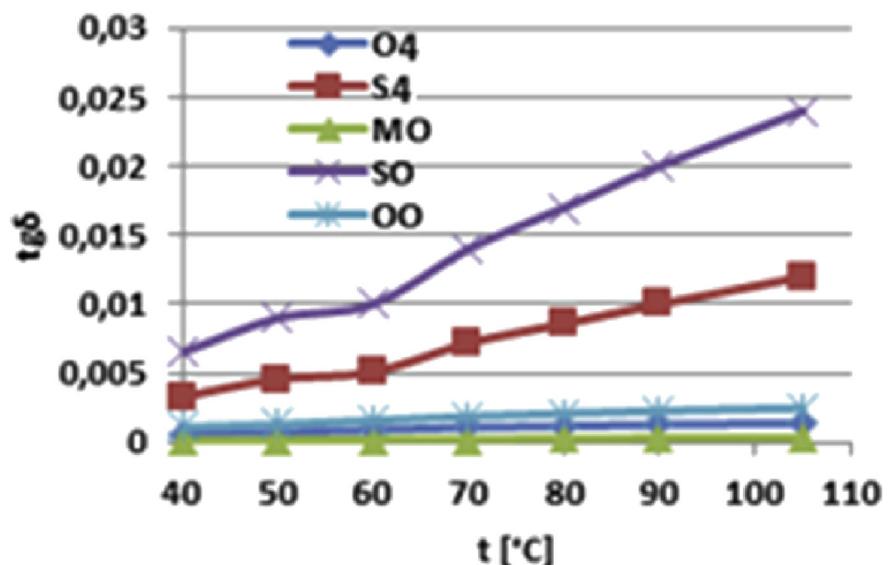


Fig. 7. Evolution of $\text{tg}\delta$ in terms of temperature for different types of insulating liquids.

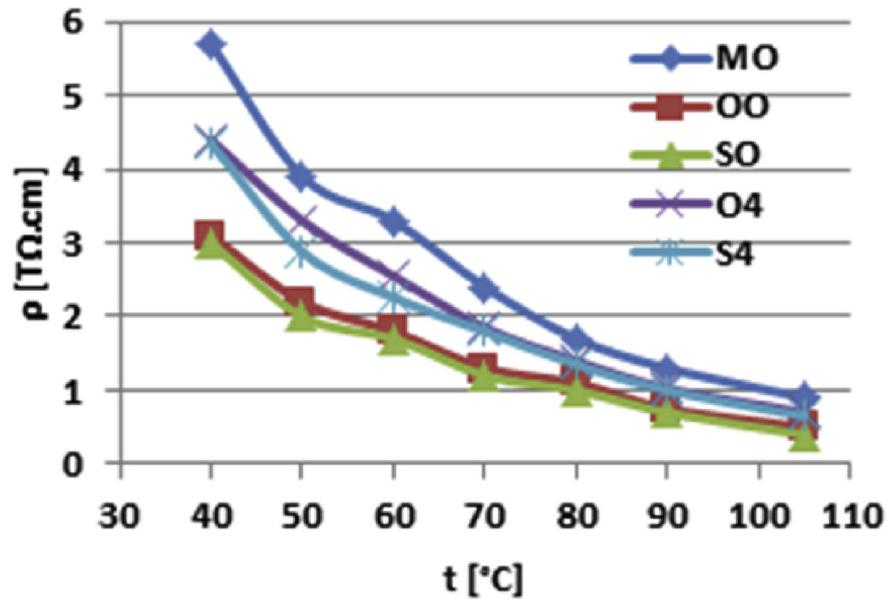


Fig. 8. Evolution of the resistivity of the insulating liquids in terms of the temperature.

from the temperature of 70 °C to the temperature of 105 °C. It is noticed that the two natural esters OO and SO have the lowest values of resistivity in comparison with the other tested insulating liquids.

3.5. Conductivity

The conductivity is certainly one of the most important physicochemical factors of insulating liquids. For the tested insulating oils, Fig. 9, we note that the conductivity of these oils depends on the temperature which increase leads to an increase in the

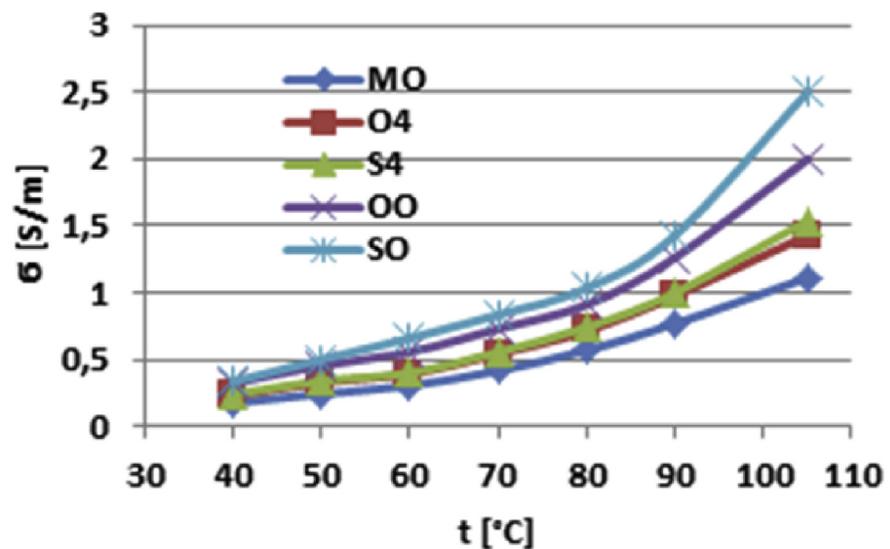


Fig. 9. Evolution of the conductivity of the insulating liquids in terms of the temperature.

conductivity of these insulating liquids. From the figure, the difference of the conductivity in terms of the temperature of the two mixtures O4 and S4 are reduced and is not remarkable. For these two mixtures O4 and S4, it is also worth noting that the conductivity values obtained in terms of temperature are close to those of MO which has the lowest values between the tested liquids. Fig. 9, shows that sunflower oil is the most conductive followed by that of olive oil and this can be explained by the high presence of ions in these liquids.

3.6. Viscosity

The viscosity of five different insulating liquids MO, OO, SO, O4 and S4 is measured under different temperatures 40 °C, 60 °C and 90 °C. For the different liquids (Fig. 10), the highest viscosity is observed at a temperature of 40 °C. The increase in temperature is accompanied by a decrease in the viscosity of these liquids.

We note that the viscosity of the liquid SO is about four times higher than the viscosity of the liquid MO under different temperatures. For olive oil, the figure shows that the viscosity value under the lowest temperature (40 °C) is too high and can reach ten times the viscosity of MO under the same temperature which makes the flow of this liquid difficult in low temperatures. These results, as shown in the figure, allow us to conclude that olive oil is not suitable for cooling transformers mounted in a cold climate but it is acceptable for our existing climate in Tunisia. Under a temperature of 90 °C, the classification of the tested liquids according to the lowest viscosity of each of them is as follows: MO, S4, O4, SO and OO. From the measurements obtained, it is found that the two mixtures S4 and O4 respectively occupy, under the highest temperature 90 °C, the second and third place after MO oil regarding the flexibility in flow.

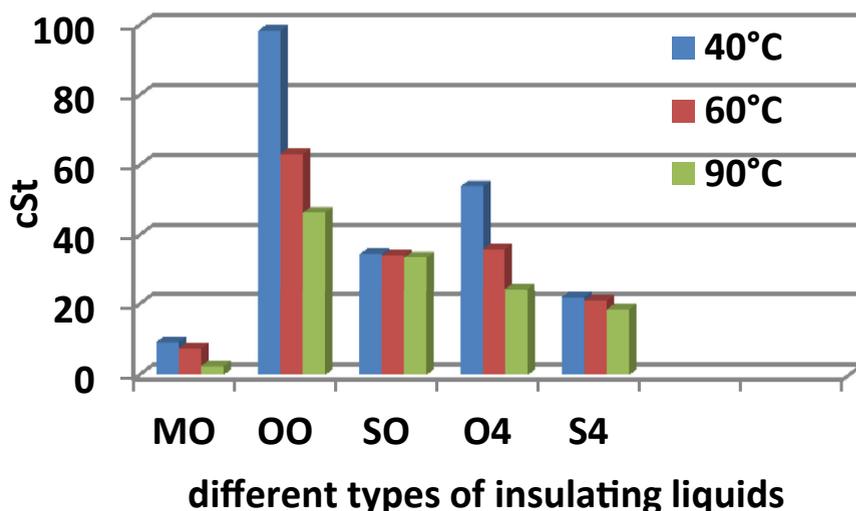


Fig. 10. Evolution of the viscosity of insulating liquids in terms of temperature.

4. Conclusion

In this work, it is proved that vegetable oils, OO and SO, have higher breakdown voltages than those of a naphthenic mineral oil. The results obtained also showed that, at the beginning of the ageing cycle, the olive oil has the best breakdown voltage followed by that of the O4 mixture and that, from the 30th day of ageing, the best breakdown tension of O4 is compared with all the other tested insulating liquids. It is shown that the electrical field intensity of electro-convection initiation of the different oils (MO, OO and SO) and oil mixtures, O4 and S4, decreases with increasing ageing time. Too, the flexibility of these Insulating liquids in movement in an electrical field is more remarkable for an MO than for the O4 and S4 mixtures.

The tests carried out show that the dissipation factor $\text{tg}\delta$ of MO is the lowest in comparison with those of the other tested insulating liquids. Indeed, with the increase of the temperature, the difference of the values obtained of $\text{tg}\delta$ for MO and the two mixtures O4 and S4 is reduced but the best dissipation factor still remains for MO. We have also shown that, with increasing temperature, the resistivity of these insulating liquids decreases and that the best resistivity is obtained for MO followed respectively by O4, S4, OO and SO. Depending on the temperature, the difference in resistivity between the two vegetable oils is not of great importance. It is worth noting that, among the tested insulating liquids, the least conductive liquid in terms of temperature is MO while for the two mixtures O4 and S4, the conductivity values obtained with the increase in temperature do not differ much and approach those obtained for MO.

The studies carried out have allowed us to show that the vegetable oils, OO and SO, have too high viscosities in comparison with the viscosity of the naphthenic oil (MO). We have also found that the O4 and S4 have acceptable viscosities under high temperatures. In the conclusion, the mixture O4 can be used as an alternative to mineral oil in power transformers installed in countries that have non-cold climates.

Declarations

Author contribution statement

Jilani Rouabeh, Lotfi M'barki: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Amor Hammami: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ibrahim Jallouli: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Ameni Driss: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors thank; the Faculty of Sciences of Gafsa- Tunisia and Electric Transport Base of Gafsa-Tunisia, BTEGF-STEG.

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