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Influence of Dielectric Liquid Type on Partial-Discharge Inception Voltage in Oil-Wedge-Type Insulating System under AC Stress

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Abstract: This article describes the results of laboratory tests on an oil-wedge-type electrode system, which were supplemented by FEM (finite element method) simulations. The studies were focused on the comparison of the partial-discharge inception voltage (PDIV) in the abovementioned system when immersed in different liquid dielectrics, namely inhibited mineral oil, uninhibited mineral oil, synthetic ester, and natural ester. In addition, the electric field stress obtained from the simulations was used in each case to determine the safe level for the actual transformer insulation. The studies were performed under AC voltage. Both electrical and optical detection methods were applied in order to properly determine the discharge inception. The statistical analysis of the results obtained from the laboratory measurements was carried out using Weibull distribution. We found that both mineral oils demonstrated better properties than the ester liquids in terms of resistance against partial-discharge appearance under the conditions of the oil-wedge-type electrode model. Therefore, for all considered cases, the inception electric field stress obtained from the FEM-based simulations corresponding to the partial-discharge inception voltage was found to be significantly higher than the commonly accepted safe design level, which is in the range of 10–12 kV/mm. This proved the good electrical strength of all liquids under test.

Keywords: dielectric liquids; partial discharges; oil wedge; synthetic ester; natural ester; mineral oil; AC voltage

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1. Introduction

Nowadays, manufacturers and buyers of power equipment increasingly decide on ecological solutions. This choice is mainly driven by a growing ecological awareness and a greater pressure to contribute to environmental protection. An ecological approach is also reflected in the transformer market, where the fundamental insulating material used in power transformers and other high-voltage devices is a dielectric liquid [1–4]. Over the past few decades, mineral oil has been the most commonly used dielectric liquid [4,5]. This is due to its good insulation, cooling, and impregnation properties and low price in relation to other solutions. However, mineral oil has a relatively low flash point (150 °C) and a low level of biodegradability, which makes it a non-eco-friendly product, especially if it leaks from the transformer or ignites due to failure. The abovementioned environmental parameters of mineral oil limit its use in special applications. Therefore, in recent years, synthetic and natural esters, which are alternatives to mineral oils, have been increasingly used in industry [1–6]. This is because esters have much better fire protection properties, i.e., they have a higher flash point and are readily biodegradable. Due to these advantages, esters have become the subject of a wide range of studies, in which the parameters of esters have been compared with the analogical parameters of mineral oils [1–10]. One of the most significant parameters characterizing the dielectric features of liquids for electrical purposes is the partial-discharge inception voltage (PDIV), which constitutes a key factor for comparison [7–10]. The PDIV is also a particularly important indicator in the process of insulation coordination at the transformer design level.

Most of the studies concerning new dielectric liquids have been focused on determining the AC breakdown voltage as a parameter that allows the evaluation of the AC dielectric strength. In this kind of measurement, the AC voltage is increased rapidly until reaching breakdown, and the so-called pre-breakdown stage, at which partial discharges develop, is not assessed [10–12]. However, in the actual insulating systems of power transformers, pre-breakdown phenomena occur, and these phenomena are solely responsible, in most cases, for the damage to the transformer's insulation system. In ester-based insulation systems, the behavior of the partial discharges under AC voltage (for example, partial-discharge inception) has not been widely studied, especially using models close to the insulation structure of a transformer. In other words, the studies are mainly limited to electrode systems with a so-called free liquid gap, which vary greatly from real insulating structures, where "electrodes" always co-operate with paper or pressboards. Although ester-based liquids have a similar AC breakdown voltage to mineral oils, or higher when they are moistened [1,3,13], it has not been unequivocally confirmed that esters also have a higher PDIV compared to the mineral oils typically applied in power transformers. The above statement, to some extent, is true when comparing the experimental results obtained for free liquid gaps and non-uniform fields [3,4,8,13], but in the case of insulation systems with so-called oil wedges, which are present in the actual insulation structures of power transformers, no clear data are available.

Hence, the present study considered the oil-wedge-based electrode model, with the PDIV assessed both electrically and on the basis of the light emitted by developing discharges. In addition, the analyses were supplemented by an electric field stress evaluation based on the finite element method (FEM). Our aim was to provide new findings that may be used by the manufacturers and operators of transformers filled with ester liquids when designing insulation structures for the power transformers.

The structure of the paper is as follows. In Section 2, the methodology of the study is described, with subsections including the definition of an oil wedge, the specification of the materials used in the experiments, and the methodology of the measurements. In Section 3, the results for both the laboratory experiments and the electric field simulations are presented together with the main findings. Finally, in Section 4, the conclusions are formulated.

2. Methodology

2.1. Oil Wedge Definition

The insulation system of a power transformer is very complex. Thus, manufacturers need to know the exact dielectric strength of each compound (dielectric material) in the system as well as the electric field stress of each part (at each point). The structure of an insulating system is not ideal, which means that undesirable areas such as oil wedges may exist. One of the most critical places for the occurrence of these small oil layers is the main duct of a power transformer, where the local electric field stress becomes very high. More precisely, the oil wedge may be located between a mounting rib and a pressboard barrier. An example of this phenomenon is shown in Figure 1 [14].

As mentioned above, the local electric field stress at this specific point in the transformer's insulating structure is higher than in the surrounded area and, in some cases, can exceed the safe design level. Since oil wedges are more susceptible to the capture of impurities and gas bubbles, the possibility of the initiation and development of partial discharges in this area is intensified.

To recreate the oil wedge presented above, the electrode system shown in Figure 2 was established. It consisted of a mushroom-type high-voltage electrode with a radius of 12 mm, a 2 mm thick pressboard barrier, and a grounded plate electrode 200 mm in diameter with 2 mm radius rounded edges. The oil wedge considered existed between the high-voltage mushroom electrode and the pressboard barrier.

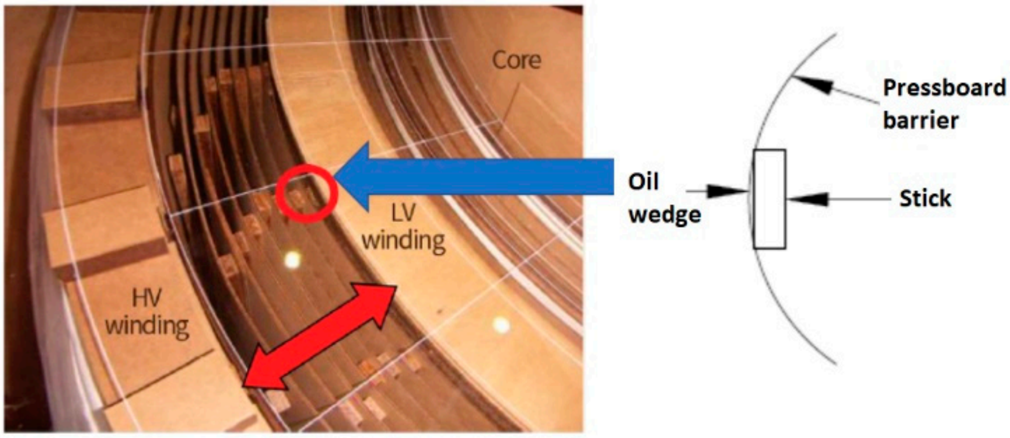

Figure 1. Example of the place of occurrence of an oil wedge in a transformer [14].

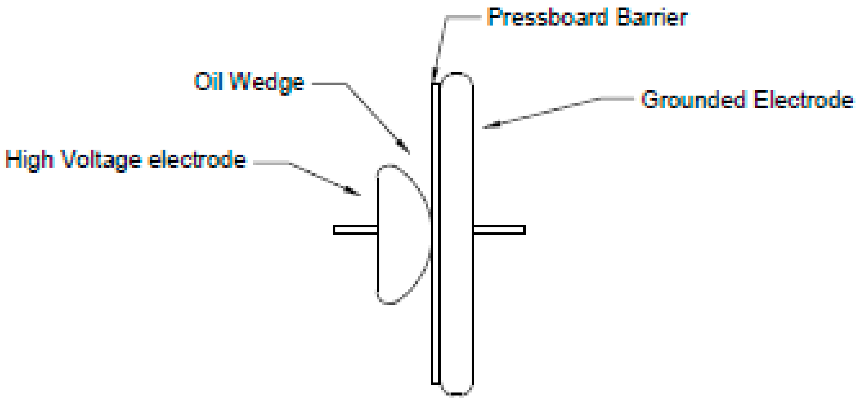

Figure 2. The model electrode system for the oil wedge considered in this study.

2.2. Materials Used in Experiment

During the measurements, pressboard samples with dimensions of 200 × 200 × 2 mm were used. These samples were first cut from a larger board and then subjected to the process of drying and impregnation. The process of drying and impregnation was conducted as follows:

(1) Drying the pressboard for 24 h under vacuum (pressure < 100 Pa) at a temperature of 105 °C;
(2) Filling the vacuum chamber in which the pressboard was placed with a given dielectric liquid at a temperature of 80 °C (under vacuum conditions);
(3) Impregnation under vacuum at a temperature of 80 °C for 24 h;
(4) Cooling the pressboard samples to ambient temperature in dielectric liquid and leaving them in liquid for another 16 h.

Table 1 summarizes the basic properties of the fresh pressboard used in the experiment.

Table 1. Basic properties of the pressboard.

Parameter	Unit	Value
Density	kg/dm^3	1.09
Dielectric constant	-	4.5
Tensile strength—lengthways	N/mm^2	107
Tensile strength—breadthways	N/mm^2	77
Conductivity of water extract	mS/m	3.3
Moisture containment	%	4.2
Ash containment	%	0.3

Twenty pressboard samples were prepared for the tests, five for each liquid considered: naphthenic uninhibited mineral oil (MO-U), naphthenic inhibited mineral oil (MO-I), natural ester (NE), and synthetic ester (SE). The basic properties of these liquids, taken from the datasheets, are listed in Table 2.

Table 2. Properties of dielectric liquids used in the experiment.

Parameter	SE	NE	MO-I	MO-U
Density at 20 °C (kg/dm^3)	0.97	0.92	0.87	0.87
Viscosity at 40 °C (mm^2/s)	29	37	7.6	9.5
Flash point (°C)	260	315	142	150
Pour point (°C)	−56	−31	−63	−51
Biodegradability	Readily biodegradable	Readily biodegradable	Inherently biodegradable	Inherently biodegradable
Own measurements				
Breakdown voltage (kV)	78.3	77.9	84.1	86.2
Moisture content (ppm)	44	52	3	2

In addition, the quality of the liquids were verified by our own laboratory measurements based on parameters such as the AC breakdown voltage (according to the IEC 60156 Standard) and the moisture content (measured using the Karl Fischer method).

2.3. Measurement Methodology

The measurements were carried out using the setup presented in Figure 3. The AC source was a testing transformer with a nominal voltage of 100 kV and a nominal current of 1 A. The transformer was connected to a capacitive voltage divider with a ratio of 1000 through a limiting resistor of 10 kΩ resistance. This setup, without a connection to the test cell, was PD-free up to 80 kV of generated voltage. This meant that the apparent charge measured was lower than 2 pC.

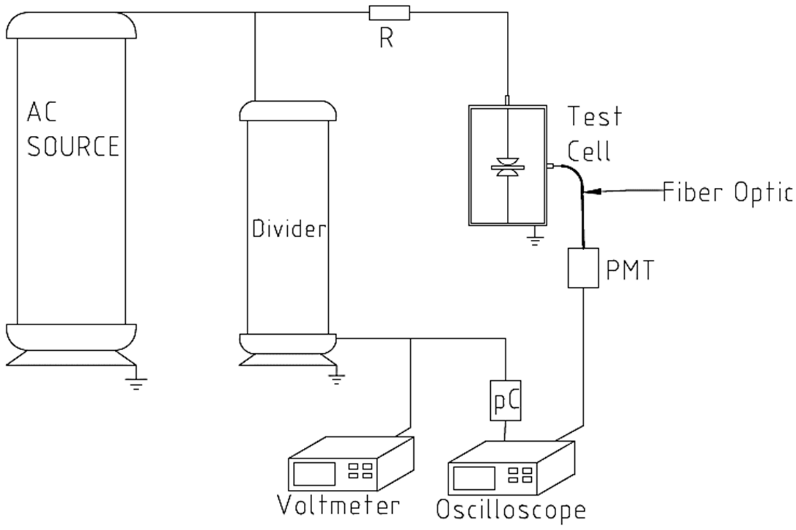

Figure 3. Experimental setup used during the measurements: R—limiting resistor, pC—quadrupole, PMT—photomultiplier.

As the literature reports [4,8,13], the criteria used to determine the PDIV may influence the conclusions drawn regarding the resistance of a given liquid against the occurrence of partial discharges in the testing conditions considered. Hence, in this study, we decided that the detection of partial discharges was to be based on two signals recorded simultaneously. The first was a current signal from the coupling quadrupole connected to the voltage divider. This signal was recorded by an oscilloscope after a calibration procedure. Thus, a typical electrical method was applied for the PD detection [15–17]. The second signal was a light signal collected by a photomultiplier (PMT). In order to effectively capture the light emitted by the discharge developing in the tested system, the end of the optical fiber cable transmitting the light to the PMT was placed over the tested model. Considering that the discharges in the analyzed model should have developed symmetrically, resembling Lichtenberg figures [18], this approach seemed to be correct for assessing the discharge initiation in the considered electrode system [19]. Taking into account the well-known fact that light pulses are consistent with current pulses [20], the parallel application of two detection methods increased the reliability of the PDIV determination in the tested electrode model. Figure 4 presents a screenshot from the oscilloscope representing the PDIV detection based on the recorded quantities.

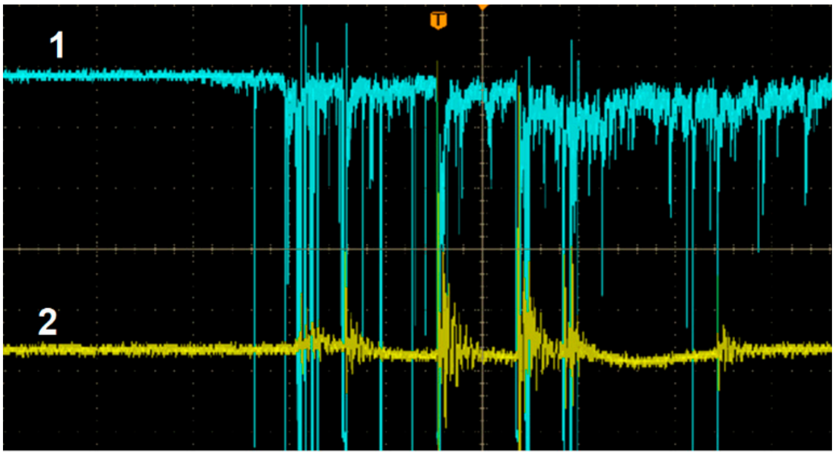

Figure 4. Example of oscillogram registered when partial discharge started to develop: 1—light signal from PMT, 2—signal from coupling quadrupole; x-axis represents time (t = 4 μs/div.), y-axis represents voltage in relative units.

Based on the literature review, we applied the Tetzner method as a measurement method [21]. Initially, for each dielectric liquid, the inception voltage for partial discharge was determined by increasing the voltage using the rising speed method up to the value when partial discharges appeared. On this basis, the initial voltage for the main tests was established as 30% lower than the value determined according to the procedure described above. From the starting value, the voltage was increased with 1 kV steps. Each voltage step lasted 60 s. The voltage increased until partial discharges were noticed. The value at which this occurred was considered the PDIV for a given case. Please note that each measurement session was preceded by the calibration of the measuring branch for the electrical method of PDIV detection. In addition, the measurement of the PD background level at maximum source voltage was carried out. The monitoring of the PD traces and light emissions was conducted in a continuous manner. When the signals appeared parallelly, this moment was recognized as discharge inception. A 15 min break was applied to ensure proper oil degassing. After 5 measurement attempts, the dielectric liquid sample was exchanged for a new one. For each tested liquid, the measurements were repeated 25 times.

3. Results

The results obtained from the measurements in the form of PDIV values were analyzed statistically using the Weibull distribution function. Weibull distribution is based on the so-called extreme value theory, which simply states that this distribution may be used for modeling the service life of complex devices or the failure-free operation of complex systems. In relation to the experiments conducted in this work, we can assume that the discharge inception voltage (inception electric field stress) functions as a kind of minimum value allowing for the long-term operation of the whole system (the insulating system of a transformer). Hence, there were no obstacles to using Weibull distribution in the analyzed case, and it may be said that Weibull distribution is suited for such applications (see, for example, [4,9,11–13,19–25]).

Figure 5 presents the Weibull distribution plots for the four considered dielectric liquids. In turn, Table 3 lists the values for a 1%, 5%, and 50% probability of discharge inception according to the obtained plots together with basic data, presented as average values and corresponding standard deviations.

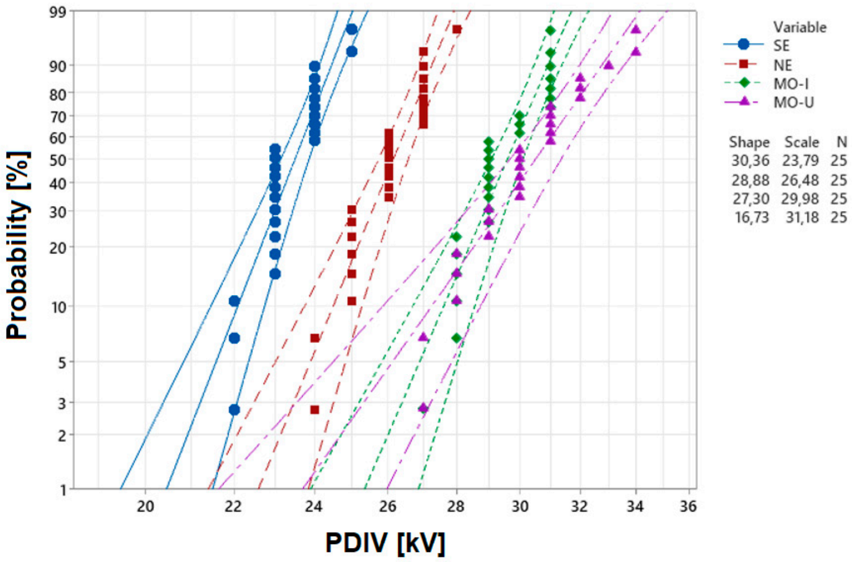

Figure 5. Weibull distribution plots of partial-discharge inception voltage (PDIV) for the distinctive liquids considered: SE—synthetic ester, NE—natural ester, MO-I—inhibited mineral oil, MO-U—uninhibited mineral oil. Shape—shape parameter of Weibull distribution function, Scale—scale parameter of Weibull distribution function, N—number of random variables.

Table 3. Characteristic values of partial-discharge inception voltage (PDIV) (kV).

Properties	SE	NE	MO-I	MO-U
1% probability	20.4	22.6	25.3	23.7
5% probability	21.6	23.9	26.9	26.1
50% probability	23.5	26.1	29.6	30.5
Average	23.4	26.0	29.4	30.3
Standard deviation	0.8	1.0	1.2	2.05

As can be clearly seen, the discharges were initiated at different testing voltages. MO-U and MO-I were characterized by very similar PDIVs in terms of both 5% and 50% inception probability as well as the average value. However, in the case of 1% inception probability, the inhibited mineral oil presented the best performance. It is also important to point out that the standard deviation for MO-U was higher than for MO-I, which confirmed the greater unpredictability of this kind of oil. Simply put, we could conclude that the inhibitors slightly improved the liquid quality in terms of resistance against partial discharge inception.

In turn, when comparing the mineral oils with the ester liquids, we noticed that both mineral oils had significantly better properties than the ester liquids under the experimental conditions. Discharges were initiated in the esters at lower testing voltages, with worse results obtained for the synthetic ester. The results contradicted those reported in the literature [4,26], wherein the discharge inception in non-uniform fields (point-sphere gaps) occurred at similar voltages for both mineral oils and ester liquids. However, it is important to remember that a non-uniform field was applied in these studies, while herein the electric field tended to be quasi-uniform. Thus, the conditions of the experiment evidently influenced the results obtained.

Since the measurement results could not be treated as the only area of comparative assessment for the tested insulating liquids, especially when only the PDIV was evaluated, the electrical field distribution was investigated using the oil-wedge-type electrode system previously applied in the laboratory experiment. Thus, the model prepared had the same dimensions (including the thickness of the pressboard and the curved parts of the electrodes) as the electrode system used in the experiment. The calculations were carried out based on the finite element method and with the use of the commercial software FEMM 4.2.

The material properties were taken from the data sheets shared by the manufacturers. The following data were used:

- Relative electrical permittivity of natural ester—3.2;
- Relative electrical permittivity of synthetic ester—3.1;
- Relative electrical permittivity of mineral oils (both MO-U and MO-I)—2.2;
- Relative electrical permittivity of pressboard immersed in natural ester—4.7;
- Relative electrical permittivity of pressboard immersed in synthetic ester—4.6;
- Relative electrical permittivity of pressboard immersed in mineral oils—4.2.

The voltage value assigned to the high-voltage electrode of the model created for the simulation corresponded to 50% inception probability according to our measurements. Obviously, this value was specified separately for each of the liquids. The grounded plate electrode had a voltage potential equal to zero.

Figure 6 presents the model created in FEMM software, with a mesh applied for further calculations. The mesh was generated automatically by the software, with a denser mesh applied around the curved part of the components of the analyzed system. The number of nodes in each case was equal to 3973.

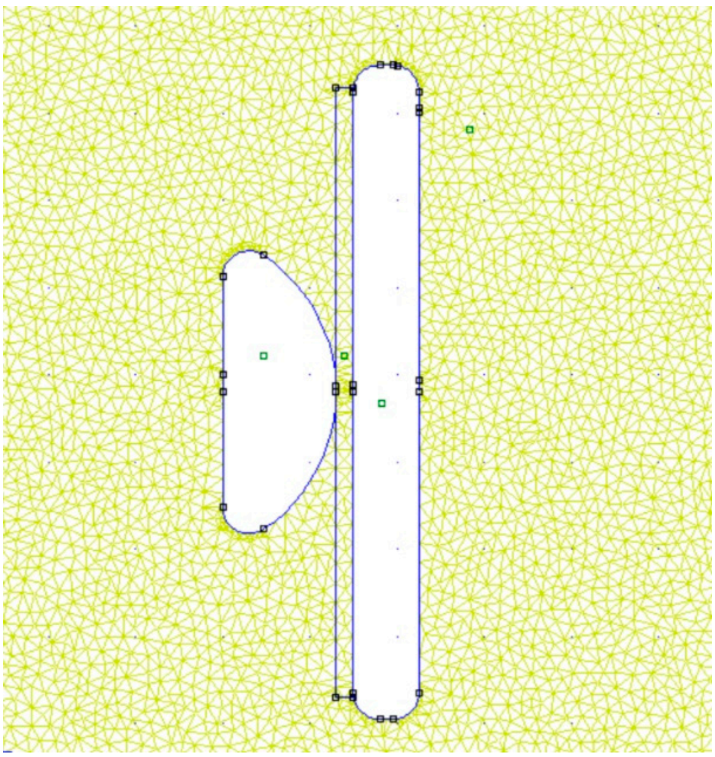

Figure 6. The model electrode system of the oil-wedge type constructed in FEMM software with applied calculating mesh.

Figure 7 shows the electric field distribution in the tested oil-wedge-based electrode model for two example cases, the mineral-oil-insulated structure and the synthetic-ester-insulated structure. In general, the results are presented in graphical form, as the graphs obtained from FEMM software did not show significant differences between the liquids considered. The colors of the oil wedge and pressboard, resulting from the local electric field, differed slightly from each other, such that the differences were visible only when comparing the esters with the mineral oils, and not when comparing the esters with each other or the mineral oils with each other. Hence, as mentioned above, only two cases are presented.

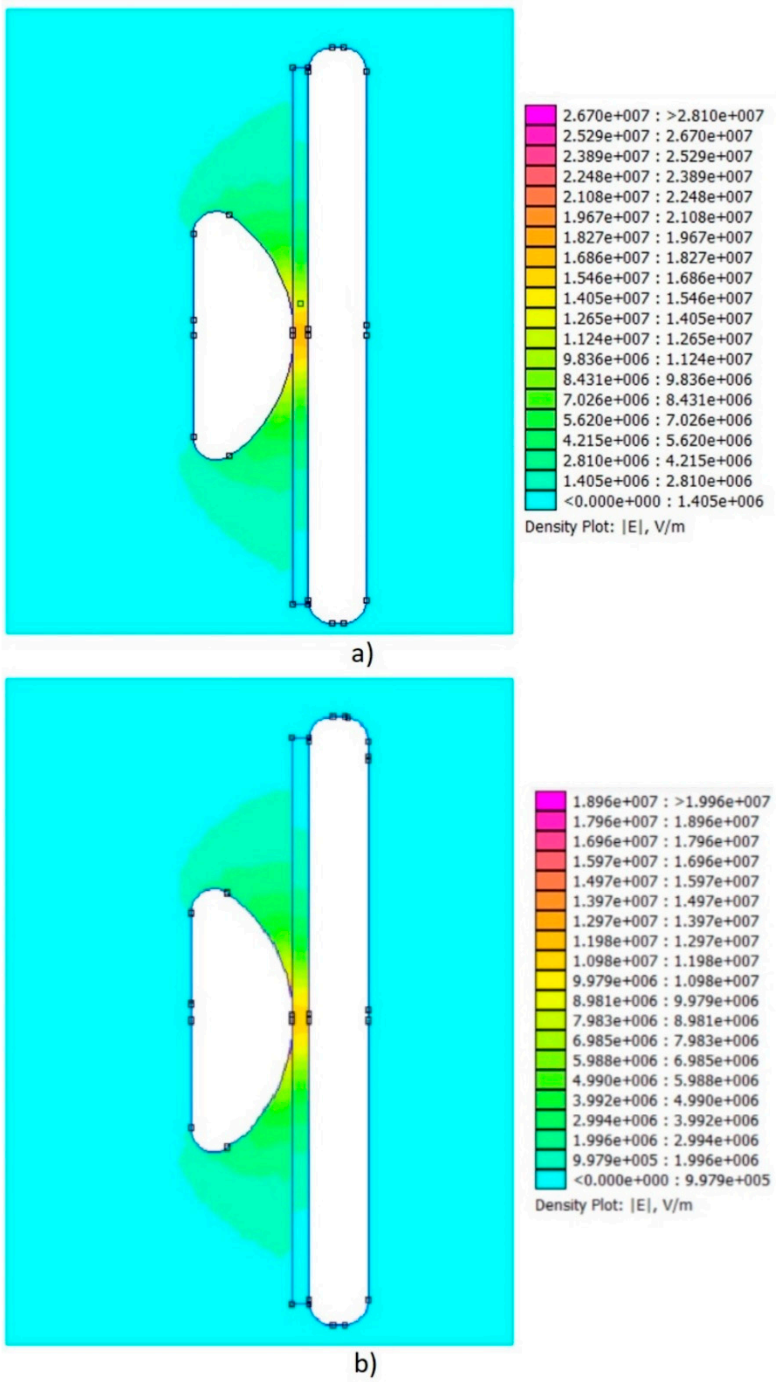

Figure 7. Electric field distribution in the model electrode system for the examples of: (**a**) mineral oil as dielectric liquid, (**b**) synthetic ester as dielectric liquid.

When the calculations were completed, as expected, the values of the maximum electric field were recorded as the values responsible for discharge inception in the liquids. However, these values could only be recognized when the numerical data from the simulations were compared. Thus, it was confirmed that in the oil wedge system tested, the so-called "weak points" were located solely in the liquid, in the area commonly known as the triple point (electrode–pressboard–liquid) [4,16,27].

Table 4 sets out the results of the maximum electric field for all four considered dielectric liquids.

Table 4. Maximum value of electric field stress in oil wedge in (kV/mm) corresponding to inception voltage from previous measurements.

SE	NE	MO-I	MO-U
19.30	21.40	34.96	36.10

Figure 8 summarizes in a graphical form the abovementioned results of the maximum electric field stress in the liquids corresponding to the PDIV values. This summary clearly shows that a higher PDIV resulted in a higher maximum electric field stress in the liquid in the considered electrode model. In addition, based on the fact that the tested liquids (mineral oils versus ester liquids) were characterized by different electrical permittivity levels, the differences between them in terms of electrical field stress were strengthened by a well-known phenomenon, i.e., that the introduction of a dielectric liquid with a higher electrical permittivity (ester instead of mineral oil) into the insulating system causes an increase in the electric field in solid insulation and a decrease in liquid insulation [3,9]. Hence, the inception electric field stress was much lower in the case of the ester liquids than for the mineral oils. In other words, in the considered cases, the discharge inception in mineral oil took place at higher local electric field stress values, confirming the more effective properties of mineral oils, even if the AC BDV of the liquids themselves is higher in the case of ester liquids.

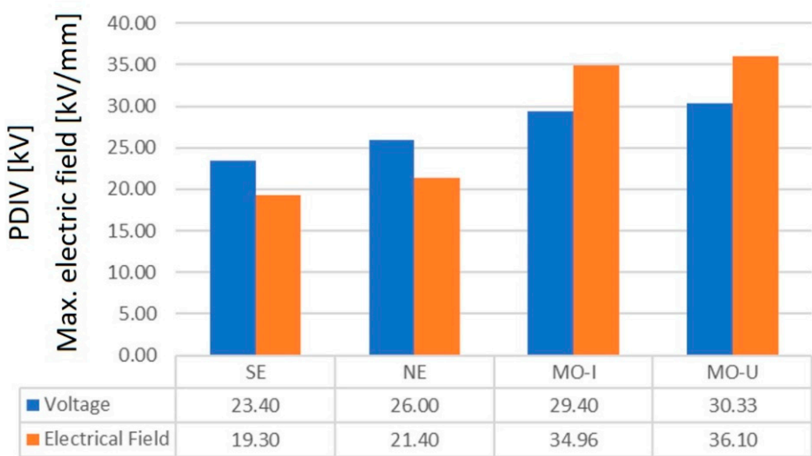

Figure 8. PDIV and maximum electric field in the oil wedge for the tested electrode model.

4. Conclusions

The main aim of this paper was to compare four different dielectric liquids in terms of partial-discharge inception voltage and related phenomena. On the basis of the experiments performed, the following conclusions could be drawn:

(1) The performed laboratory measurements proved that partial-discharge inception always takes place in the oil wedge (triple point). The start of the discharges was always accompanied by a strong light signal.

(2) The inception electric field of the partial discharges obtained under the conditions of the experiment was significantly higher than the commonly accepted safe design level, which is in the range of 10–12 kV/mm. This proved the high electrical strength of all liquids under test. Nevertheless, it should be mentioned that the tested liquids were produced under so-called laboratory conditions, being devoid of any impurities and with a water content below 3 ppm in the case of mineral oil and around 40 ppm in the case of ester liquids.
(3) Alternative liquids were characterized by slightly lower PDIV values in comparison to both mineral oils considered (non-inhibited and inhibited). However, they fulfilled the abovementioned safe design levels of electric field stress. Hence, we can treat them as alternative liquids to mineral oils, but special care should be taken regarding their quality and the electric field stress that could occur in the insulating structure when designing transformers intended to be filled with ester liquids.
(4) The results also showed that the lower inception electric field stress value in the case of the alternative liquids was determined by their higher electrical permittivity (3.1 and 3.2, respectively, for natural and synthetic esters). However, it is important to remember that the globally higher electrical permittivity of esters reduces the difference in the electrical field stress between the solid and liquid insulation in transformers.
(5) It seems that the next stage of this research could be focused on assessing the inception voltage and inception electric field stress of the same group of liquids under normal manufacturing/service process conditions. In addition, the tests should be repeated and extended with studies at lightning impulse voltage, because the quality of insulation systems at very small insulation distances, i.e., with oil wedges, is still not fully understood, but it is an important issue from the viewpoint of engineering practice.
(6) After completing tests at lightning impulse voltage, the results could be used as design criteria for the insulation systems of power transformers, in order to increase the reliability of the created projects and reduce the failure ratio in the future.

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