Electr Eng (2017) 99:179–186
DOI 10.1007/s00202-016-0408-z

ORIGINAL PAPER

Influence of volume effect on electrical discharge initiation in mineral oil in the setup of insulated electrodes

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Received: 9 April 2015 / Accepted: 9 August 2016 / Published online: 23 August 2016

Abstract This article deals with the problem of electrical discharge initiation in mineral oil in the setup of insulated electrodes. The results of laboratory experimental studies were collated with the results of the numerical calculations of electrical field stress. Both kinds of the research methods were applied to analyze the two model electrode setups immersed in mineral oil: setup with insulated HV electrode and setup with bare HV electrode having the same outer dimensions as the insulated one. The obtained similarities in the values of maximum inception electrical field stress and the equality in the experimentally evaluated initiation delay indicated that the most stressed oil volume and weak points included in it may be responsible for discharge initiation in paper–oil insulation setups with oil of technical purity. The same number of weak points included in oil may be, in both the cases considered, an equally productive source of initiation sites.

Keywords High voltage insulation · Electrical discharges · Mineral oil · Volume effect · Electrical field · Inception voltage

1 Introduction

The studies on electrical discharge initiation in dielectric liquids have been conducted for many years. In these studies, initiation has been considered both in pure hydrocarbon liquids and in transformer mineral oil of technical purity [1–9]. A new part of the experimental studies has been focused also on environmentally friendly dielectric liquids such as the natural and synthetic esters [10–12]. The most often analyzed electrode setups have been the point-plane setups representing extremely non-uniform electrical field distribution. The typical voltage waveform used in the studies on discharge development in dielectric liquids has been the lightning impulse of different characteristic times. Taking into account that mineral oil is the most important liquid from the practical point of view, the largest number of the studies has been focused solely on it. The wide spectrum of research indicated that electrical discharge initiation and propagation are very complex processes involving different physical phenomena. Depending on the chemical composition and physical properties of the liquids, pressure and temperature, type of testing voltage as well as electrode geometry, the processes determining discharge initiation may be the bubble formation by Joule heating, cavity formation by electromechanical forces or electrostatic emission [1,3,4,7,8]. Discharge propagation may be, however, the result of ionization of gas included in discharge channel (development of slow 1st and 2nd mode discharges) or direct liquid ionization as a characteristic process of the development of 3rd or 4th mode discharges. This second type of ionization occurs when the voltage significantly exceeds (more than two times) the 50 % breakdown voltage for the given electrode gap [1–5,9–12]. Similar phenomena to these, observed in the setups of bare electrodes of point-plane arrangements, were recorded for electrode setups in which an HV electrode was covered by paper insulation. In such setups, characterized by quasi-uniform electrical field distribution, discharge characteristics were practically the same as in the case of setups with high degree of field non-uniformity [13–17]. Thus, the phenomena responsible for electrical discharge initiation and development may be considered as the same as in the setups with electrodes without paper insulation.

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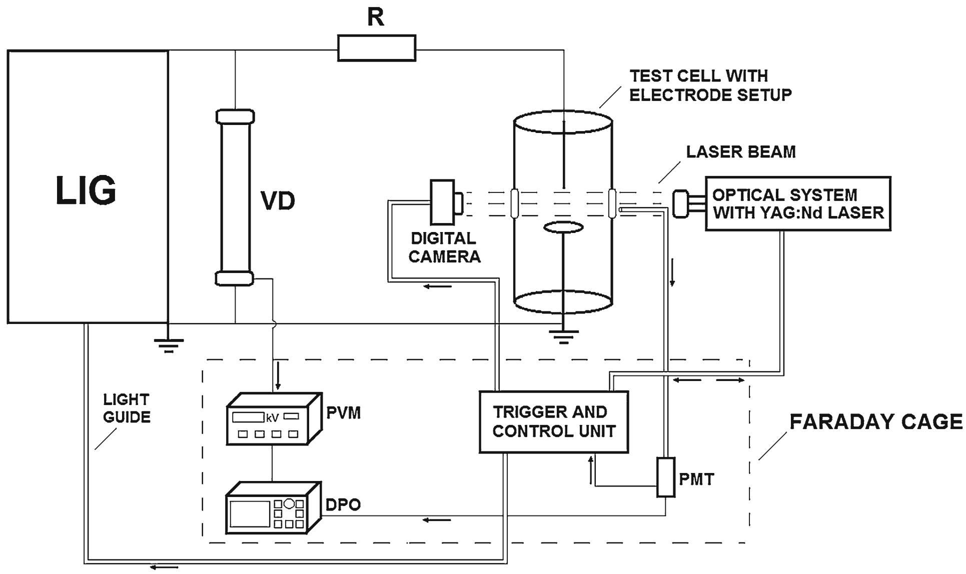

Fig. 1 Laboratory experimental system: *LIG* lightning impulse generator, *VD* voltage divider, *R* limit resistor, *PMT* photomultiplier tube, *PVM* peak value meter, *DPO* digital phosphor oscilloscope

Additionally important phenomenon, that is responsible for discharge initiation in oil, is a well-known volume effect of the most stressed oil. According to the theory of this phenomenon, electrical discharges in oil may be initiated in oil volume being under electrical field stress higher than 90 % of maximum value for given electrode setup. This means that the more the impurities or gas bubbles in considered oil volume, the probability of discharge initiation gets higher. On the other hand, increasing the most stressed oil volume causes a decrease in the electrical strength of the insulating system exponentially [8,14,18]. Hence, taking into account the existing knowledge in the field of discharge initiation and propagation in mineral oil, confirmation of the phenomenon responsible for such the initiation in the setups of paper–oil insulation and with oil of technical purity became an aim of the studies presented. These studies were divided into two parts: laboratory experiments and numerical calculations of electrical field distribution. The results of performed experiments and their discussion were limited to one parameter—the most important from the initiation of discharges point of view—time to initiation. This parameter informs about the delay of the moment of initiation in relation to the moment of supplying the lightning impulse to the electrode setup. On the other hand, simulation of electrical field distribution was focused on the determination of maximum electrical field stress occurring in investigated electrode setups at inception voltage.

2 Laboratory studies

The main aspect of the experimental laboratory studies was the assessment of the influence of paper insulation on the parameters characterizing the electrical discharges developing in mineral oil in the setup of insulated electrodes. Selected parameters to analysis were inception voltage, time to discharge initiation and propagation velocity. Simultaneously, the spatio-temporal development of the discharges was observed on the basis of taken-out shadowgraph photos and registered light oscillograms [16,17]. The research was performed in an automated laboratory system consisting of two experimental systems cooperating together. This laboratory system is presented schematically in Fig. 1.

In the first system, the single-shot shadowgraph method with the Q-switched YAG neodymium laser as a flash lamp was used to record the photos of the discharge forms. In the second system, a photomultiplier tube and a digital storage oscilloscope were used to register the light pulses emitted by the developing discharges. Trigger and control unit was, however, responsible for the detection of discharge initiation and for measuring the time to discharge initiation [12,16,17].

Two model electrode setups used in the experimental studies are presented schematically in Fig. 2.

The HV electrode in the first setup was insulated by crepe paper while in the second setup this electrode was bare having the same outer dimensions as the electrode with insulation. Both the setups were characterized by a quasi-uniform electrical field distribution. In both setups, the HV electrode was a brass wire formed in the shape of the capital letter U. In the case of the setup with the insulated HV electrode, the wire had a 4 mm diameter while in the case of the setup with a bare HV electrode 4.8 mm. The 0.8 mm difference (0.4 mm from each side) resulted from the thickness of the insulation made of the crepe paper, which was used to cover the thinner wire creating, in this way, the insulation on HV electrode. This meant that in both the cases identical outer dimensions of the HV electrode were obtained. The part of the electrode setups connected with grounded electrode was, however, identical.

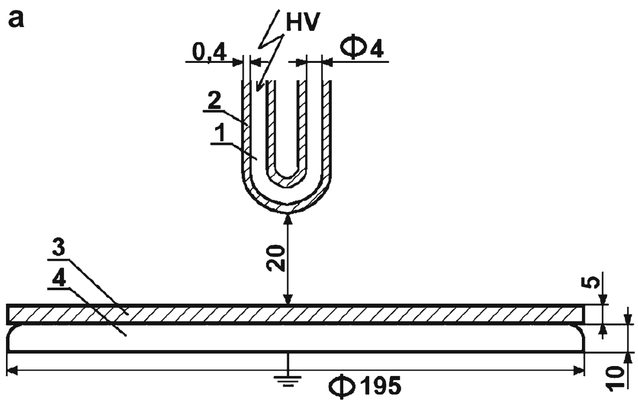

Fig. 2 Electrode setups used in laboratory experimental studies: *1* HV electrode (*brass wire*), *2* paper insulation, *3* transformerboard insulating plate, *4* grounded electrode

The grounded electrode was constituted of a metal plate of 195 mm in diameter. On this plate, 5 mm in thick, a transformerboard insulating plate was deposited. This was made to prevent against complete breakdown which, emitting very intensive light, could destroy the sensitive optical devices used in the measurements. Both the setups were immersed in the test cell filled by commercial mineral oil of technical purity. The studies were performed under the standard lightning impulse voltage of characteristic times 1.2/50 µs produced by Marx generator. Both positive and negative polarities were used during the investigations [14,16,17].

As mentioned above, the time to initiation (t) was a main parameter considered from the initiation of discharges point of view. This time was measured with an accuracy of 0.1 µs as the time between the moment of supplying the lightning impulse to the given electrode setup and the beginning of the discharge determined by the system of discharge initiation detecting. This latter was based on measuring the light emitted by discharge channels. The moment of initiation was marked as the first light pulse generated by the developing discharge and registered by the photomultiplier tube installed in the system of light registration [12,16,17]. Example of recorded time course on which the method of time to initiation evaluation was presented is shown in Fig. 3.

To compare the results of the measurements realized in the same field conditions, time to initiation was measured for both the electrode setups at the same value of testing voltage. This voltage was chosen as a statistically estimated inception voltage (median of measured values) corresponding to the setup with the insulated HV electrode. For positive polarity of lightning impulse, this was a value of 190 kV and for negative polarity 192 kV, respectively [16,17]. The choice of such a value resulted from the fact that for the setup with the insulated HV electrode inception voltage was higher than for the setup with the bare HV electrode. Thus, we can state with a relatively large probability that discharge initiation will follow each applied lightning impulse. On the other

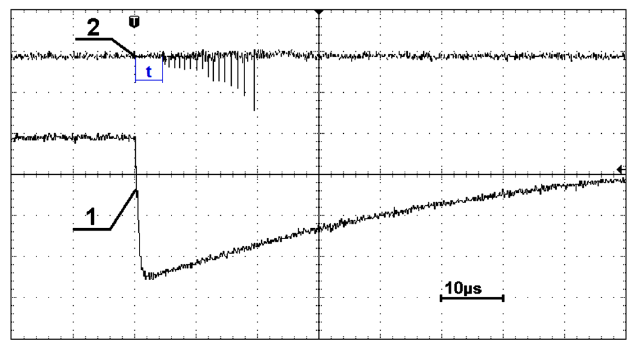

Fig. 3 Method of time to initiation evaluation: negative discharge development in the setup with bare HV electrode: *t* time to initiation, *1* voltage signal [50 kV/div.], *2* light signal [arb. units]

hand, the difference in the inception voltage between both the setups was so small and, thus, the chance on the direct initiation and then development of the fast 3rd mode discharges in the setup of bare HV electrode practically did not exist.

Statistically estimated values of times to initiation, based on the tens of individual measurements for each of voltage polarities and each of electrode setups, are presented in Table 1. These times were described by a log-normal distribution and, thus, the average values t and standard deviations σ, together with the corresponding confidence intervals, were included in the table [17,19,20].

The fundamental conclusion resulting from the Table 1 is a clearly visible lack of differences between the setup with bare HV electrode and the setup with insulated HV electrode in the estimated times to initiation of the discharges. This conclusion concerns both the positive and negative lightning impulse. The equality of the measured times relates also to the standard deviations assigned to them. These standard deviations differ to each other in a very small range. In order not to leave the conclusion about the equality of times to initiation only as the statistical assumption resulting from the intuitively interpretation of measured times to initiation, the

Table 1 Times to initiation of the discharges for considered electrode setups: *t* average value of times to initiation, σ standard deviation of average value

Voltage polarity	Type of HV electrode	Parameters (μs)		Confidence intervals (μs)
Positive (190 kV)	Insulated	t	4.9	$4.4 < t < 5.6$
		σ	1.4	$0.8 < \sigma < 2.3$
	Bare	t	5.0	$4.2 < t < 6.2$
		σ	1.3	$0.3 < \sigma < 2.9$
Negative (192 kV)	Insulated	t	4.6	$3.8 < t < 5.5$
		σ	1.8	$0.9 < \sigma < 3.1$
	Bare	t	4.7	$3.7 < t < 6.2$
		σ	1.4	$0.2 < \sigma < 3.5$

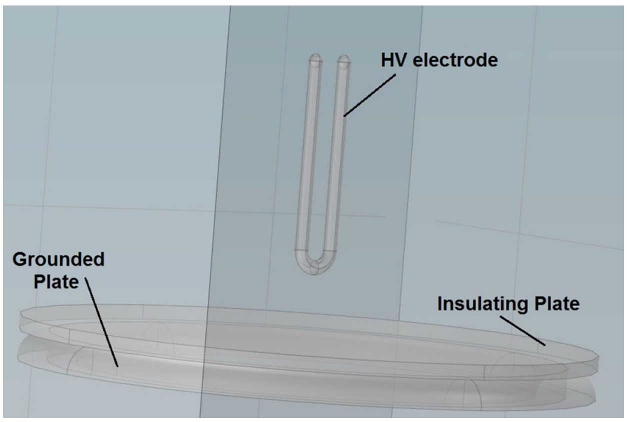

Fig. 4 Modeled setup with bare HV electrode used in simulations

hypothesis on their equality was confirmed using analysis of variance method (ANOVA). The ANOVA test showed that there was no reason to reject the hypothesis about the equality of average values of times to initiation. From the practical point of view obtained, small difference may be recognized as negligible [20].

3 Simulation of electrical field distribution

For the analysis of electrical field distribution in the investigated model electrode setups, the finite element method (FEM) applied to commercially available software was used.

The first step of the simulation was shaping, in a three-dimensional (3D) space, the electrode setups which were used previously in the laboratory experimental studies. Figure 4 presents an example of such shaping for the setup with bare HV electrode.

After shaping both the electrode setups, materials which had the same properties as the materials used in the experimental studies were assigned to the individual setup components. Then, for the individual materials, relative electrical permittivity ε_r was designed (2.2 for oil and 4 for the transformerboard insulating plate and paper insulation). Simultaneously, electrical potential was implied to the HV electrode. To simplify the calculations and taking into account the small difference between both the voltage polarities in the estimated inception voltages, the electric potential of the HV electrode taken for the simulation was 190 kV. Because in the simulations the electrical field distribution in the inter-electrode space was sought and, in other words, the value of the maximum field stress had to be found; this was assumed in the considerations that the voltage applied to the HV electrode will be characterized by DC-based type of voltage. It is a kind of simplification in relation to the actual laboratory measurements; however, according to the authors' opinion such simplification is not too far-fetched. The essence of the simulations was to determine the values of the maximum electrical field stress at lightning impulse of predetermined peak value applied to the electrode setups, which was considered as inception voltage. The highest value of the electrical field due to geometry of the electrodes and applied voltage takes place just for a moment when the lightning impulse reaches its peak value; hence, the above-mentioned assumption seems to be correct. Additionally, it is important to remind that in the works presented only moment of discharge initiation was analyzed. Thus, static simulation was performed as a fast and valuable approach. The dynamics of the changes in the voltage applied was not considered; because for the moment of initiation as well as from the point of view of the problem associated with the volume effect in oil it was not necessary [14,18]. However, future work will be focused also on the modeling related to the voltage changes over time (actual lightning impulse voltage) and to the influence of the space charge on the process of discharge propagation.

In the next step, according to the assumptions of the finite element method, a mesh of tetrahedral elements was designed for each of the distinctive cases. It was assumed that the densest distribution of tetrahedral elements creating the computational mesh had to be applied in the insulating space surrounding the HV electrode. This resulted from the expected results and knowledge on the possible discharge initiation area [13–17]. The rest of the space, for example the insulating plate, did not require a mesh of high density because in this

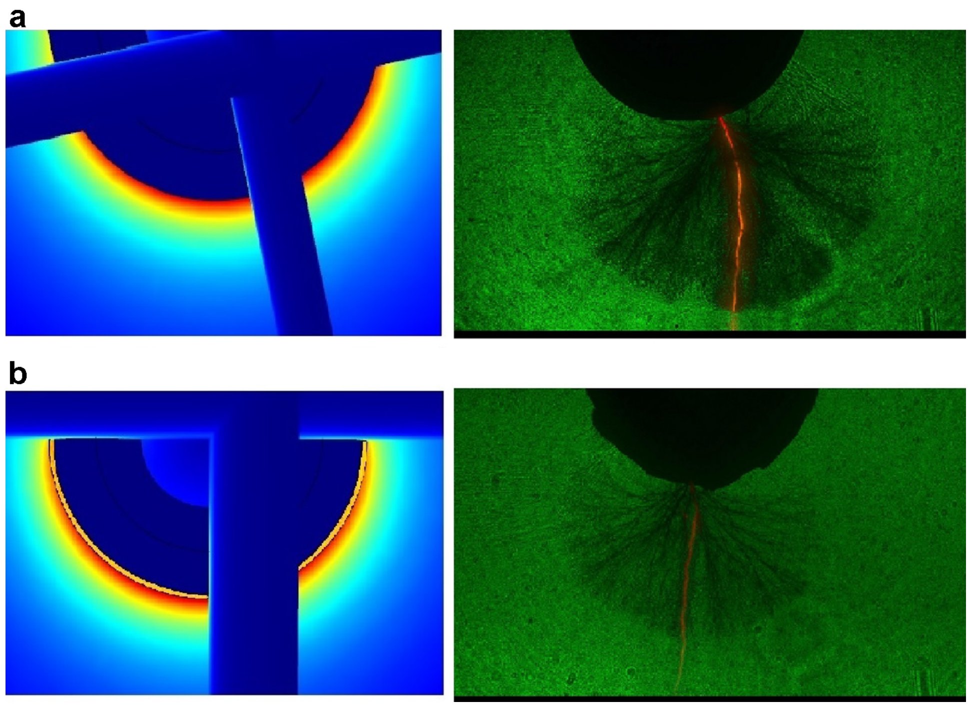

Fig. 5 Results of simulation of electrical field distribution and photos of positive discharges developing in the electrode setups under consideration at inception electrical field stress: **a** setup with bare HV electrode, **b** setup with insulated HV electrode

Table 2 Maximum values of electrical field stress E_{max} obtained on the basis of simulations

Type of HV electrode	E_{max} [MV/cm]
Insulated	0.40
Bare	0.42

space the values of electrical field stress were not important from the point of view of the considered issue. In each case, the same density of computational mesh was used to make a reliable comparison of the obtained results. The results of the simulations presenting electrical field distribution in both model electrode setups are shown in Fig. 5. The area of the maximum electrical field stress appeared in the close proximity to the HV electrode, thus, around the place where initiation of discharges in oil was observed during the experimental studies. To confirm this fact, together with the electrical field distribution the exemplary photos of discharges (positive ones) developing typically in electrode setups under consideration at inception voltage are also presented [14,16,17,19].

In the above figure, the highest values of electrical field stress are represented by the red color and its shades while the lowest values and zero by the blue color with its shades. Because the most important area for analysis was the area in close vicinity of the HV electrode, the results of the simulation present only this area in magnitude. The maximum values of electrical field stress obtained on the basis of simulations are set in Table 2.

These values, corresponding to the inception electrical field stress (not the breakdown strength because the breakdown did not happen during experimental studies), were very similar to each other. The small difference between obtained values is, first of all, a result of the small difference in the geometry of both the setups. Although the layer of insulating paper on the HV electrode is very thin, its influence on the electrical field distribution exists and this influence was anticipated before the beginning of the simulation. The border, separating the materials having different electrical permittivity (paper and oil), causes the difference in electrical field distribution. So, obtaining different maximum values of electrical field stress is mostly true in the case in consideration. On the other hand, we should take into account the fact that the outer dimensions of the metal part of both HV electrodes are also slightly different. Bare electrode had a higher diameter due to the fact that it was enlarged by a thickness corresponding to the thickness of the paper insulation covering the insulated HV electrode. Thus, it was not expected that the results will be exactly the same in both cases [8,13,18]. This expectation had its base also in the knowledge on insulation setups of series insulation. Applying the well-known Eq. (1), describing electrical field stress in such the setups:

$$E_k = \frac{V}{\varepsilon r_k \sum_{i=1}^{n} \frac{a_i}{\varepsilon r_i}} \tag{1}$$

where E_k is the electrical field stress in the given layer, V is the electric potential of HV electrode, εr is the relative electrical permittivity of the given layer, a is the thickness of the given dielectric material and n is the number of the

Table 3 Values of electrical field stress E_k obtained on the basis of Eq. (1)

Type of HV electrode	E (kV/cm)	
Insulated	Paper layer	Oil
	51.68	93.97
Bare	95.00	

layers, it may be confirmed the relationship between setups with paper insulation and without it.

Although the setups under consideration had a quasi-uniform electrical field distribution, the general dependence should be identical.

For these simple calculations the following values were assumed for the setup with an insulated HV electrode: electrical potential $V = 190\,\text{kV}$, relative electrical permittivity of paper $\varepsilon r_1 = 4$, relative electrical permittivity of mineral oil $\varepsilon r_2 = 2.2$, thickness of paper insulation $a_1 = 0.4\,\text{mm}$ and length of oil gap $a_2 = 20\,\text{mm}$. Simultaneously for the setup with a bare HV electrode the equation was simplified giving in result the so-called average electrical field stress since only applied voltage V and the length of oil gap were considered in calculations. Finally the results like in Table 3 were obtained.

As was expected, the higher value of electrical field stress in oil was obtained in the case of the setup with a bare HV electrode and still, because of the thin layer of paper insulation, the difference between both the setups was very small.

4 Discussion

Experimental laboratory studies indicated on the equality of the measured times to initiation for the considered electrode setups. On this basis, it may be concluded that the reason for this equality lies in the same source of weak points responsible for the process of discharge initiation. Because the delay of initiation is the same in both cases, it does not have to be influenced by the structure at which initiation was originated. It is hardly probable that the paper insulation and metal of the electrode are the identical sources of weak points in the tested setups. Such the source, in the setup of paper–oil insulation with the oil of technical purity, seems to be only the oil bath. This conclusion may be additionally supported by the results of another works in this field [13]. In these works, the influence of artificially implemented weak points on the electrical strength of insulation setups was investigated. The weak points of different kinds were placed in the paper insulation wrapping of HV electrode and then the inception voltage for each kind of weak points was measured separately. The result of this experiment showed that the electrical strength, understood as the value of statistically estimated location parameter of the Weibull distribution, did not decrease. From the above, it may be supposed that volume effect in oil may play an important role in the process of discharge initiation. The simulation of electrical field distribution and assignation of maximum electrical field stress confirmed the presented supposition. The calculated maximum values of electrical field stress in considered electrode setups were obtained as almost identical. They were 0.4 MV/cm for the setup with an insulated HV electrode and 0.42 MV/cm for the setup with a bare HV electrode respectively. Referring this to the identity in the outer dimensions of both the setups, it may be concluded that the most stressed oil volume in both considered cases should be also identical. Thus, in the same volume of the most stressed oil the same number of weak points occurs and these weak points cause the same delay of initiation.

Finally, in order to state the reliable values of maximum electrical field stress obtained from the simulations, these values were compared to the characteristic values of inception electrical field stress of discharges in oil. Within the literature on this subject, there are many publications, serving such threshold values of inception electrical field stress both for the setups of non-uniform electrical field distribution (point-plane) and for setups of uniform and quasi-uniform field distribution [1,3,4,6–8]. These data came from the theoretical considerations and experimental research, and also were supported by appropriate mathematical calculations. From the general point of view, these considerations have indicated that the values of inception electrical field stress of slow electrical discharges, developing in mineral oil under impulse voltage, are in the range from tenths to few MV/cm. These values, however, depend on the degree of field non-uniformity and type of liquid. In the setups of uniform and quasi-uniform electrical field distribution, inception electrical field stress is about 0.3–0.5 MV/cm (especially for the liquids of technical purity) while in the setups of non-uniform electrical field distribution and liquids of laboratory purity even few or 10 MV/cm [1–4,6–8]. In the first case, generally lower values of inception electrical field stress are the result of uniform electrical field distribution and the influence of surface and volume effect on the electrical strength of such setups. In the second case, when the setups are characterized by non-uniform electrical field distribution (point-plane electrode arrangements) the values of inception electrical field stress change with the changes of radius of curvature of the HV point electrode. Lower values are observed when increasing the radius of the curvature. This may be explained by the fact that the surface of the end of the HV electrode increases, so the surface effect starts to have an influence. However, it is important to remember that increasing the radius of curvature increases the inception voltage of discharges. On the other hand, electrical strength of some hydrocarbons (electrical field stress at which in the given conditions breakdown happens) in accordance with the considerations presented in

[1] is in the range of 1–2 MV/cm. Thus, the initiation of discharges, which disappear in the interelectrode gap and do not cause a complete breakdown, should take place at much lower values than this, corresponding to breakdown electrical field stress.

Close to the dependence of inception electrical field stress on the degree of field non-uniformity (electrode configuration), this also depends on the width of the oil gap. In the case of small gaps (to 5 mm), discharge initiation is practically always connected with breakdown. Hence, electrical strength of the setup in the category of electrical field stress is equal to the inception electrical field stress [1,3]. Some papers indicate, based on theoretical considerations concerning the physico-chemical nature of the liquids, that the threshold value of inception electrical field stress is directly connected with the threshold of the phenomena of electrostatic emission or field ionization occurring in the liquid volume. In such a case, these values for field emission are from 7 to 20 MV/cm (compared by recording the direct current), wherein they depend on the radius of curvature of point electrode. With a larger radius of curvature and lower electrical field stress, the phenomena of critical volume were observed, and this phenomenon was assessed as decisive in the process of discharge initiation. Concerning the field of ionization, the proper values of electrical field stress, at which this ionization may take place, were assessed on 10 to several MV/cm. For example, a higher electrical field is needed in the case of cyclohexane, for which the ionization energy is 8.75 eV while for mineral oil, consisting mostly of aromatic compounds, the threshold electrical field stress causing ionization may be lower, because the ionization energy of benzene is circa 7 eV (benzene ring is a main part of aromatic hydrocarbons, which are included in mineral oil). However, it is important to note, that above presented values for field emission and field ionization correspond only to ideal liquids, for which the consideration did not take into account the possibility to contain in their volume impurities or gas bubbles [1,4,6,7].

On the basis of the above-presented data, it is clearly visible that for the model electrode setups of quasi-uniform electrical field distribution obtained values are in accordance with the common approach to the issue of discharge initiation in liquid dielectrics. For the setups of the electrical field distribution close to uniform, literature data of inception electrical field stress are from 0.3–0.5 MV/cm to about 1 MV/cm while the values correspond to the model electrode setups representing quasi-uniform electrical field distribution are in the range of 0.4 MV/cm. Taking into account additionally that both the surface of the electrode and the surface of the insulation wrapping were shaped as ideal in the simulations (without any irregularities causing locally the increase of electrical field stress) the obtianed values may be treated as a fully reliable.

5 Conclusions

The above presented considerations concerning relationship between experimentally measured times to initiation of the discharges in oil and the results of simulations of maximum electrical field stress allowed for presentation of the following conclusions:

1. The most stressed oil volume and the weak points included in it may be successfully responsible for discharge initiation in mineral oil of technical purity. This does not depend on whether the HV electrode is covered by paper or it is without this wrapping. This conclusion results from the equality of experimentally measured in the same testing conditions times to initiation and practically identical values of maximum electrical field stress obtained for both considered model electrode setups through FEM simulations. However, this conclusion does not diminish the role of paper insulation in the initiation process. This insulation repels the initiation sites out of the region of high field stress. This is only a confirmation of the feasible and correct approach regarding the special allowance for the quality of insulating oil used in high voltage insulating systems with paper–oil insulation.
2. It is possible to initiate the electrical discharge in the setup of insulated electrodes with quasi-uniform electrical field distribution in mineral oil at maximum electrical field stress in the range of 0.4–0.5 MV/cm. This is especially possible for oil of technical purity which has impurities being able to constitute the weak points of the setup and then to determine its electrical strength.

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