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Streamer propagation in a non-uniform electric field under lightning impulse in short gaps insulated with natural ester and mineral oil

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Abstract. This article describes the comparative experimental studies on streamer propagation in natural ester and mineral oil under a high voltage lightning impulse. These studies were concentrated around the small electrode gaps and the point-plane electrode arrangement. The spatial shapes of the developing streamers, light emission and propagation velocity were analyzed and compared between the two different dielectric liquids. In both of them two streamer propagation modes were registered during the studies performed. Propagation of slow 2nd mode streamers took place below the so-called acceleration voltage while fast 3rd mode streamers developed at acceleration voltage and above. Comparing the streamer shapes corresponding to a given voltage polarity, no visible differences were observed between the liquids tested. Concerning the light emission, higher frequencies of light pulses were registered however in the case of natural ester. The significant differences between both liquids were noticed in the value of the acceleration voltage estimated. In the case of positive polarity streamers started to develop in natural ester as a 3rd mode at lower value of testing voltage than in the case of mineral oil. For negative polarity, within the applied testing voltages, 3rd mode streamers appeared only in natural ester. On this basis, the fundamental conclusion is that natural ester may have a lower ability of preventing the development of fast and energetic 3rd mode streamers, even at small electrode gaps.

Key words: natural ester, mineral oil, lightning impulse, streamer propagation, light emission.

1. Introduction

Ecological trends are observed in many branches of electrical power engineering. Hence, these trends could not be omitted also in terms of insulating liquids used in power transformers. This is primarily due to the fact that mineral oil commonly used as an insulator and cooler in transformers, is not an environmentally neutral fluid. In case of an unintended release to the environment, mineral oil may constitute a potential threat to the soil and watercourses. For this reason, some new fluids were introduced to the transformer market as an alternative to mineral oil in order to mitigate the environmental hazard. Such issue is particularly important when transformer applications have to be implemented in places of restrictive regulations in the area of fire prevention and environmental protection. Ones of such the fluids are natural esters. In relation to mineral oil, they are characterized by better environmental properties (above 95% of biodegradability compared to only 10% characteristic for mineral oil) and higher fire point (above 300°C) providing their fire-resistant nature [1–5].

Natural esters, apart from having environmentally friendly properties, also have relatively good features concerning their dielectric characteristics. In terms of electrical strength at AC stress, natural esters are characterized by the lack of influence of moisture content, up to 300 ppm, on the AC breakdown voltage. Besides, natural esters have the ability to absorb water from insulating paper, which is desirable from the point of view of paper aging. Additionally, higher electrical permittivity of natural esters than that of mineral oils results in a more uniform electrical field distribution in paper-dielectric liquid insulating system [6–10].

Despite many positive features of the natural esters, the studies, which have been focused on streamer propagation under lightning impulse (LI) voltage, have indicated the lower ability of esters in prevention against the development of fast and energetic streamers [11–14]. Because the number of studies in this field is not large and knowledge is not sufficient to determine clearly which of the liquids behave better under LI stress, authors' studies have just been focused on this aspect and have been presented in this paper in terms of short electrode gaps.

Overall, the assessment of streamer propagation in natural esters has been commonly based on the comparison of streamer characteristics between esters and mineral oils, taking into account that the phenomena of streamer initiation and propagation in mineral oil are basically well recognized. Generally, it is a well-known fact that streamers in dielectric liquids may develop as a slow (1st and 2nd mode streamers) or fast (3rd and 4th mode streamers) and which of propagation mode occurs, depends on the value of testing voltage, thus on the value of local electrical field. It may be stated that lower values of electrical field stress (from tenths of MV/cm to 10 MV/cm) cause the development of slow propagating streamers while higher values of electrical field stress (from tens to even 100 MV/cm) may initiate propagation of the fast, high energy streamers [14–18]. Both types of above mentioned propagation modes have been described by different streamer characteristics, among them the most important seem to be the propagation velocity, streamer shapes and structures, as well as current and light time-dependent waveshapes. Especially important in description of propagation modes of the

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streamers is a value of the voltage, at which the change of propagation mode occurs. This value has been called the acceleration voltage (and marked commonly as V_a) and has been related to the value of inception or breakdown voltage for given electrode setup. The accepted name "acceleration voltage" comes from the fact that the streamers, after exceeding above mentioned value of voltage, rapidly change their propagation velocity from few to tens of km/s [11, 17]. It is important to notice that the change of propagation velocity entails the change of the spatial shape of the streamers and the recorded waveshapes of current and light. Thus, assignation of acceleration voltage for different dielectric liquids and simultaneous observation of the streamer characteristics for different values of testing voltage may allow for the assessment of the differences and similarities between them [12, 13].

2. Experimental techniques

The natural ester used in the studies was a commercial liquid produced from the soya bean. The chemical composition of the liquid used was a mixture of relatively polar triglycerides (long-chain fatty acid-ester molecules) which have some degree of instauration and readily form hydrogen bonds. Comparatively, the studies were performed also for mineral oil of naphthenic type. In both cases the liquids tested filled 26 liters in volume the test cell in which the point-plane electrode setup was placed. The high voltage (HV) electrode was a tungsten point with radius of curvature of 250 μm while the grounded electrode was made of an aluminum plate of 150 mm in diameter. On the plane electrode a 5 mm thick pressboard sheet was deposited, in order to prevent the complete breakdown in the investigated setup. The tested electrode gaps (free oil space between HV point and insulating plate) were 15 and 20 mm respectively. The electrode setup was supplied from a Marx generator, which produced the high voltage standard lightning impulse 1.2/50 μs. Both negative and positive polarity was used. The measurement of peak value and shape of voltage waveform was achieved using a resistive voltage divider, peak value meter and digital oscilloscope. The measurement techniques were the techniques that are commonly used in the studies of streamer propagation in dielectric liquids [11–13, 15–17]. In details, the techniques used in the presented studies were described in [19, 20]. The single-shot shadowgraph method (with an YAG:Nd laser as a flash lamp) was used to record the images of the streamers. This meant that one photo might be recorded during streamer development. The moment of taking the photo was controlled with a delay time (t) which could be changed from 0.3 μs to any set-point value. This time was related to the theoretical beginning of the discharge assessed as a moment in which first light pulse emitted by the initiated streamer was detected by a photomultiplier. Additionally, static photos could be and were recorded in the selected cases. In turn, the above mentioned photomultiplier was used to register the light emitted by the developing streamers. By using such a sensitive instrument the assessment of the intensity of ionization processes occurring during streamer development were possible [21, 22]. On the basis of the photos recorded and the light oscillograms collected, propagation velocity of the streamers was statistically estimated.

The streamer features were registered in a wide range of testing voltages related to the statistically evaluated inception voltages (V_i). The subsequent voltage levels, at which streamer characteristics were registered, were just the multipliers of the inception voltage. A 0.2 V_i step was assumed during the studies. A maximum inception voltage multiplier was however set on 2.4 V_i. Such a procedure allowed assigning the acceleration voltage as the direct multiplieres of the inception voltage for a given electrode gap and a given voltage polarity.

Before beginning the experiment the basic dielectric parameters (AC breakdown voltage, dielectric dissipation factor, moisture content) of both liquids were measured in accordance with the specific IEC standards. The criteria for AC breakdown voltage and the dielectric dissipation factor were fulfilled by both the liquids tested with following values: 64 kV and 0.0016 for mineral oil and 71 kV and 0.044 for natural ester [23, 24]. The moisture content was also on the satisfactory level at 9 ppm and 37 ppm for mineral oil and natural ester respectively. Confirmation of this fact was a lack of the influence of this factor on the AC breakdown strength of both liquids.

The schematic view of a laboratory system used in the studies was presented in Fig. 1.

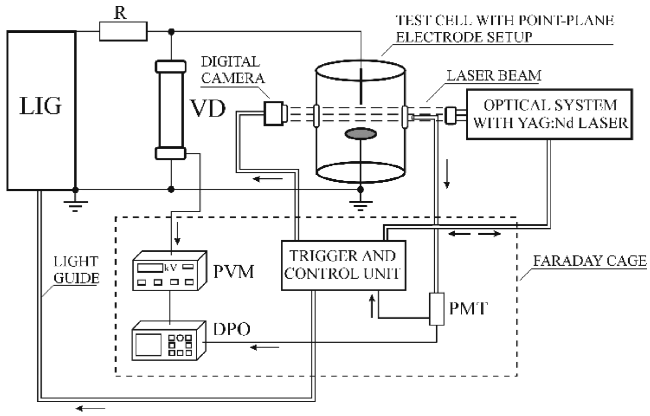

Fig. 1. Laboratory experimental system: LIG – lightning impulse generator, VD – voltage divider, R – limiting resistor, PMT – photomultiplier tube, PVM – peak value meter, DPO – digital phosphor oscilloscope

3. Results of the studies

3.1. Inception voltage. The inception voltages were estimated using a step method with a 2.5 kV voltage increment. Due to the statistical nature of prebreakdown phenomena in liquids 15 measurement procedures of the inception voltage estimation were repeated for each of the liquids tested and both voltage polarities [14]. Thus, 15 individual values were taken into account to analyse statistically the inception voltage parameters. In each on the distinctive procedures the fact of discharge development at given value of testing voltage was determined both on the basis of streamer photos (appearance of streamer channels on the photo recorded) and light oscillograms (appearance of individual pulses on the light waveshape recorded). The obtained results of statistical estimation of inception voltages for the considered gap distances 15 and 20 mm and both polarities of lightning impulse were presented respectively in Table 1 and 2. The statistical distribution function used to describe the inception voltages was a Weibull distribution function given by formula (1) with location parameter V_0, scale parameter V_m and shape parameter k. Additionally a median of inception voltages V_{Med} was calculated and included in these tables

$$F(V) = 1 - \exp\left[-\left(\frac{V - V_0}{V_m - V_0}\right)^k\right]. \qquad (1)$$

Table 1
Weibull distribution parameters for positive inception voltages

Type of liquid	Gap distance [mm]	V_0 [kV]	V_m [kV]	k	V_{Med} [kV]
Natural ester	15	52.1	58.1	2.6	57.3
	20	57.6	63.9	2.0	62.8
Mineral oil	15	52.5	61.2	3.8	60.4
	20	53.7	64.7	3.4	63.5

Table 2
Weibull distribution parameters for negative inception voltages

Type of liquid	Gap distance [mm]	V_0 [kV]	V_m [kV]	k	V_{Med} [kV]
Natural ester	15	52.7	57.7	2.2	57.3
	20	56.7	64.1	2.6	63.1
Mineral oil	15	51.2	59.4	3.1	58.5
	20	54.2	65.0	3.4	63.9

The results of estimation were also presented in the form of Weibull distribution curves. This was done in order to achieve a better comparison of the results obtained. Figure 2 presents these results separately for positive and negative polarity.

The results obtained were analyzed also from the point of view of inception electrical field stress. In order to calculate this quantity a well-known formula (2) was used

$$E_i = \frac{2V_i}{r \cdot \ln\left(\frac{4d}{r}\right)}, \qquad (2)$$

where E_i – inception electrical field stress, V_i – inception voltage, d – electrode gap, r – radius of curvature of HV point electrode [15, 16, 25, 26].

The above formula has been commonly used to calculate the value of inception electrical field stress on the basis of electrode setup size and value of the inception voltage measured. As was mentioned above the typical values of inception electrical field stress oscillate between 0.5 and 10 MV/cm. This oscillation is associated with the varying radius of curvature of point electrode from 10 mm to 1 μm. The difference noticed results from the so-called surface area effect. When the surface of a HV electrode increases (by the increase of radius of curvature) the probability of defects on the surface of electrode also increases. This is because the potential defects may cause an increase of the local electrical field and may do easier the way to streamer initiation. However it is important to notice that in many of the studies the values of electrical field stress were calculated as the values at which breakdown occurred. In such a case the values of electrical field stress are higher than at inception voltage therefore they are close to the upper limit (10 MV/cm) [15, 17].

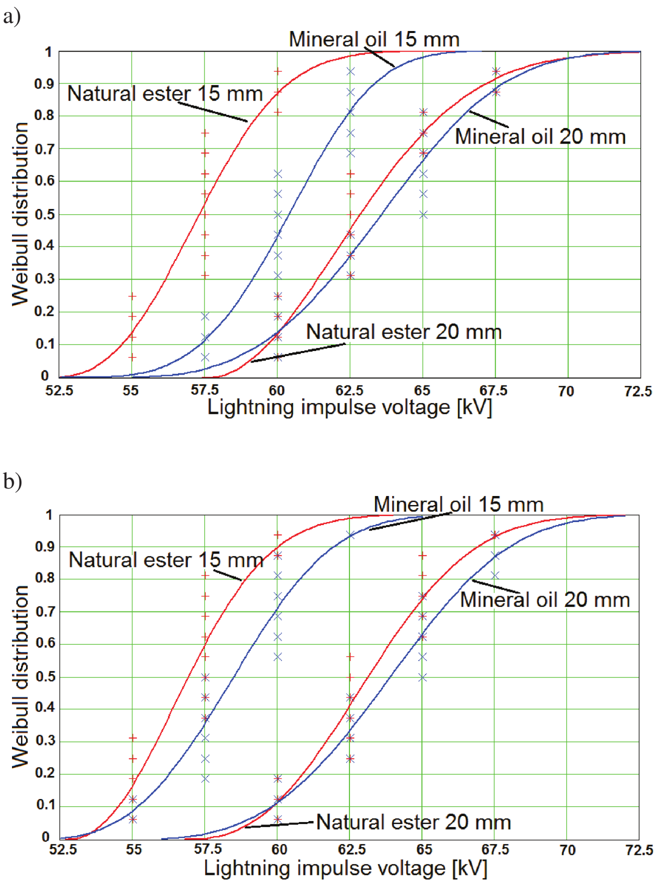

Fig. 2. Weibull distribution function of inception voltages for positive (a) and negative (b) lightning impulse voltage

In the studies presented for the inception electrical field calculations the following data were used: distance between the electrodes "d" (15 and 20 mm respectively), radius of curvature of HV point electrode "r" equal to 250 μm and distinctive inception voltages estimated (the values of medians). The results obtained, presented separately for both of the gaps, each of the liquids tested and both voltage polarities, were set in Table 3.

Table 3
Inception electrical field stress calculated on the basis of formula (2)

Type of liquid	Gap distance [mm]	E_i [MV/cm]	
		Positive polarity	Negative polarity
Natural ester	15	0.836	0.836
	20	0.871	0.875
Mineral oil	15	0.882	0.854
	20	0.881	0.886

These results (electrical field stress between 0.8 and 0.9 MV/cm) were consistent with the literature data indicating that initiation of the streamers, which do not lead to complete breakdown (so-called “stopping length” streamers), may occur at the values of electrical field stress close to 1.0 MV/cm [25, 26]. The type of insulating medium did not influence on inception electrical field stress.

The similarities between both the liquids were noticed not only on the level of their inception voltages and inception electrical field stress but also in the case of typical streamer characteristic as the spatial shapes of the streamers recorded photographically, oscillograms of the light emitted and propagation velocities. Figure 3 presents the images of streamer shapes recorded respectively at positive and negative LI.

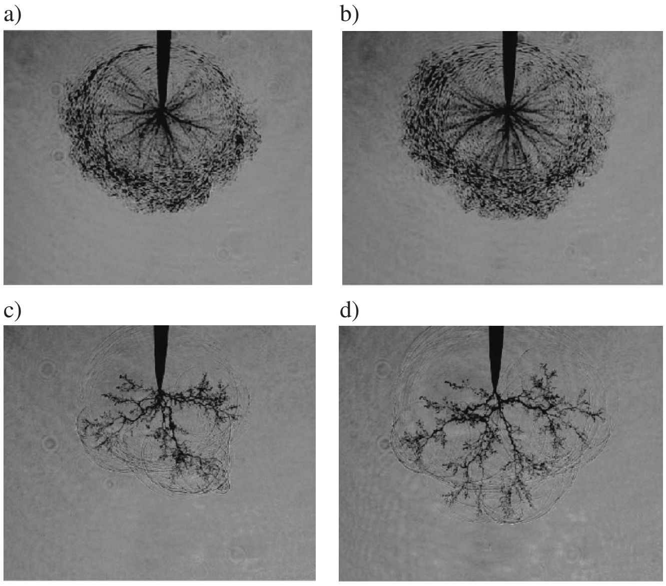

Fig. 3. Examples of recorded shapes of 2nd mode streamers developing at inception voltage, $V_i = 60$ kV, $d = 15$ mm: a) positive polarity, natural ester, $t = 2.2$ μs, b) positive polarity, mineral oil, $t = 2.1$ μs, c) negative polarity, natural ester, $t = 3.9$ μs, d) negative polarity, mineral oil, $t = 4.2$ μs

The observed structure of the positive streamers for both liquids and both electrode gaps formed a bush of a spherical boundary of rising radius as the streamer developed. In the case of negative streamers they resembled the compact bushy structure with many branches propagating mainly lateral but also paraxial directions [11–13, 17–19]. During the streamer propagation shock waves were noticed both under positive and negative voltage stress. These electrohydrodynamic phenomena were the result of impact of streamer channels on liquid and movement of liquid due to the hydrodynamic forces [19, 22, 27]. This phenomenon concerned in the same extent the tested mineral oil and natural ester.

Figure 4 shows however the magnified fragments of the typical light waveshapes collected at inception voltage respectively for positive and negative polarity. Comparing these oscillograms, this may be noticed that the sequences of light pulses are similar for both the liquids tested. These light pulses increase with propagation time and disappear after few or several microseconds. Both in the case of positive and negative polarity there are the typical “stopping length” streamers, which do not touch the opposite, grounded electrode [11, 13, 14, 17, 22]. The propagation of such streamers is stopped due to the low electrical field existing at some distance from the HV point electrode and low impact of space charge coming from the streamer itself. One characteristic feature of the oscillograms compared is definitely lower frequency and lower peak values of the light pulses corresponding to the streamers in mineral oil. Such dependence was generally observed for all registered oscillograms. However, conclusions in this field must be formed carefully because they do not take into account the different absorption coefficients of the liquids tested. Anyway, higher frequency of light pulses may be understood as an easier way for the next propagation step leaving the charge carriers of both polarities in the interelectrode space. The charges influence on the process of re-ignition of the streamers by influence on the value of actual electric field which depends not only on the instantaneous value of the testing voltage but also on aforementioned surface and space charge densities. This may be supposed that re-ignition, which requires restoration of the former field stress, in the case of both the liquid tested occurs in a different way.

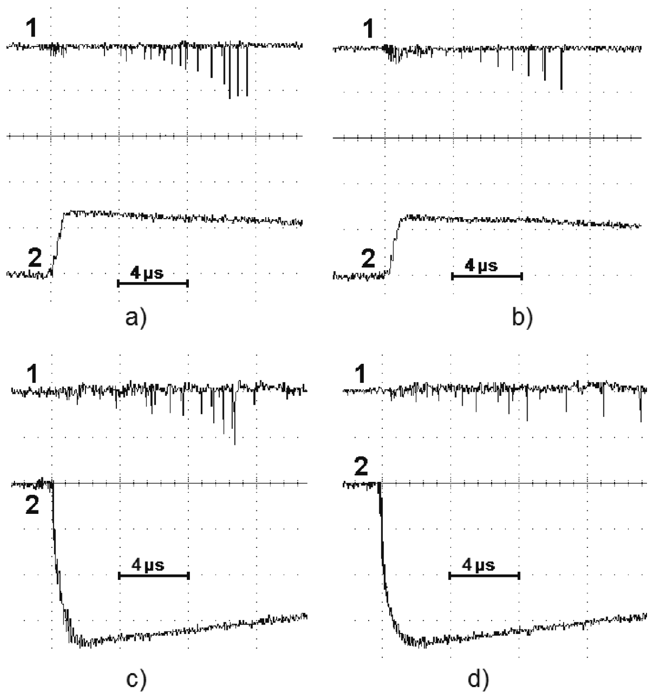

Fig. 4. Typical light oscillograms recorded during propagation of 2nd mode streamers at inception voltage $V_i = 65$ kV, $d = 20$ mm: a) positive polarity, natural ester, b) positive polarity, mineral oil, c) negative polarity, natural ester, d) negative polarity, mineral oil; 1 – light [arb. units], 2 – voltage: [50 kV/div.] – for subfigures a & b; [20 kV/div.] – for subfigures c & d

Table 4 includes the results of estimation of the propagation velocities of streamers developing at inception voltage. These velocities were determined to be the slope of the regression line in $l = f(t)$ co-ordinate system. The “l” signified the length of the longest streamer channel measured photographically and "t" was the above mentioned delay time meaning moment of taking the photo.

Table 4
Statistically estimated propagation velocities of the streamers developing at inception voltage

Electrode gap	Voltage polarity	Propagation velocity [km/s]	
		Natural ester	Mineral oil
15	–	0.81	0.77
	+	2.09	1.99
20	–	0.82	0.71
	+	2.06	2.08

The obtained values of propagation velocities are typical for slow developing 2nd mode streamers. The well-known relationships between propagation velocities of positive and negative streamers were also noticed. These connected with positive polarity were close to a 2 km/s while the velocities corresponding to the negative streamers were lower than 1 km/s [11, 13, 15–20, 22].

3.2. Propagation modes. The next stages of the studies were focused on findings concerning the voltages higher than inception voltage. Taking into account quite similar values of the medians of the inception voltages obtained for distinctive electrode gaps, a reference value for inception voltage multipliers was established respectively as a 60 kV for 15 mm gap and a 65 kV for 20 mm gap. Thus, considering that the step increase in the voltage was assumed as a 0.2 of V_i, the voltage increment in an absolute value of voltage was respectively 12 kV for 15 mm gap and 13 kV for 20 mm gap. Simultaneously, the maximum value of the testing voltage (corresponding to the inception voltage multiplier equal to 2.4) was established as 144 kV and 156 kV respectively.

In Table 5 the values of testing voltages being the multipliers of inception voltage are summarized.

Table 5
Real values of testing voltages being the multipliers of inception voltage

Voltage multipliers	Peak value of lightning impulse [kV]	
	15 mm	20 mm
V_i	60	65
1.2 V_i	72	78
1.4 V_i	84	91
1.6 V_i	96	104
1.8 V_i	108	117
2.0 V_i	120	130
2.2 V_i	132	143
2.4 V_i	144	156

In order to achieve statistically reliable results, the 20 LIs of both polarities were applied to the electrode setup for each of the liquids tested and at each of the voltage levels. On the basis of 20, obtained in this way photo-oscillogram pairs, propagation velocity was estimated for given inception voltage multipliers. The method of assessment of propagation velocity depended on the type of streamer which developed. When streamer did not touch the insulating pressboard sheet placed on grounded electrode propagation velocity was assumed identical with the procedure described in the case of inception voltage. When streamer touched the insulating sheet propagation velocity was estimated as the relationship between the electrode gap (d) and time (t) after which the developing streamer reached this sheet. This moment was clearly visible on the light oscillograms registered as a wide light pulse at the end of the series. This pulse represented the light emitted by the surface discharges developing over the surface of insulating plate and light of the return discharge forming itself as a result of capacitive coupling between HV electrode and grounded electrode [19].

Two propagation modes were found during the studies performed, both for positive and negative streamers. According to the system proposed by Lesaint and Massala in [17], recorded streamers were assigned to the 2nd or 3rd mode respectively. Which of the developing streamer belonged to the specific mode was determined mainly on the basis of evaluated propagation velocity and confirmed by the photographically recorded streamer shapes and the light waveshapes registered.

A good method to present the results of the consideration regarding the propagation modes in tested natural ester fluid and mineral oil is relationship between propagation velocity and testing voltage [11–13, 17]. In authors' approach voltage axis was presented as the inception voltage multipliers with the designation of specific values of voltage that were important in the comparative analysis of behaviour of the liquids tested. Figure 5 shows the above mentioned relationship for the 20 mm electrode gap and both liquids for positive and negative LI voltage respectively. Each of the points in the figures corresponds to the average propagation velocity for the given inception voltage multiplier.

a)
b)

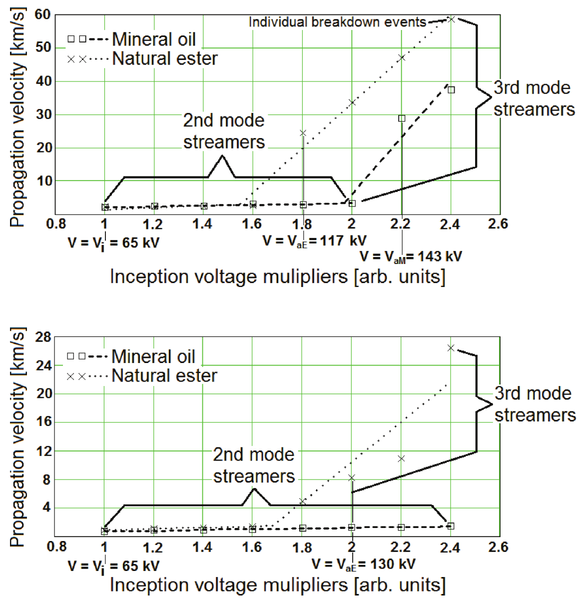

Fig. 5. Dependence of propagation velocity of the streamers versus multiples of inception voltage for 20 mm electrode gap: V_i – adopted inception voltage, V_{aE} – acceleration voltage of the streamers in natural ester, V_{aM} – acceleration voltage of the streamers in mineral oil: a) positive polarity, b) negative polarity

An important point on the presented graphs is, mentioned in the introduction, the acceleration voltage. This indicator was designated both as an appropriate value of inception voltage multiplier and as an absolute value of testing voltage. Simultaneously, two areas were also marked in the graphs as the areas concerning the 2nd and 3rd propagation mode respectively. In the case of natural ester and positive LI voltage, for the 2.4 V_i, breakdown events were noticed a few times. This was also indicated in the corresponding graph.

The obtained results for both electrode gaps and both voltage polarities were also summarized in Table 6 and 7. The bold fonts indicate the appearance of the 3rd mode streamers.

Table 6
Propagation velocities of positive streamers for distinctive levels of inception voltage multipliers

Voltage multiples	Propagation velocity [km/s]			
	15 mm		20 mm	
	Mineral oil	Natural ester	Mineral oil	Natural ester
V_i	1.99	2.09	2.08	2.18
1.2 V_i	2.05	2.37	2.41	2.39
1.4 V_i	2.33	2.45	2.50	2.31
1.6 V_i	2.98	2.97	3.12	2.68
1.8 V_i	3.31	**19.3**	2.78	**21.8**
2.0 V_i	3.27	**32.6**	3.26	**31.6**
2.2 V_i	**26.6**	**44.8**	**28.9**	**47.1**
2.4 V_i	**42.3**	**57.1**	**37.5**	**58.5**

Table 7
Propagation velocities of negative streamers for distinctive levels of inception voltage multipliers

Voltage multiples	Propagation velocity [km/s]			
	15 mm		20 mm	
	Mineral oil	Natural ester	Mineral oil	Natural ester
V$_i$	0.77	0.83	0.71	0.82
1.2 V_i	0.83	1.04	0.80	1.01
1.4V_i	0.85	1.19	0.85	1.16
1.6 V_i	1.03	1.27	0.96	1.31
1.8 V_i	1.10	1.43	1.08	4.92
2.0 V_i	1.24	**9.96**	1.23	**8.19**
2.2 V_i	1.29	**11.7**	1.26	**10.9**
2.4 V_i	1.44	**27.9**	1.41	**26.4**

The performed measurements pointed out clearly that fast, 3rd mode positive streamers, appeared in natural ester at much lower value of inception voltage multipliers than in mineral oil. This value, which was identical for both the electrode gaps considered, was 1.8 V_i while for mineral oil this was 2.2 V_i. Relating this to the absolute value of testing voltage, found the difference between both liquids was 26 kV for a 20 mm gap and 24 kV for a 15 mm gap. The additional conclusion is that at the same values of inception voltage multipliers (the same values of testing voltages), statistically estimated average propagation velocities of the streamers developing in mineral oil were generally lower than corresponding average propagation velocities of the streamers in natural ester. Exemplary, for 20 mm gap and 156 kV of testing voltage (2.4 V_i), propagation velocity of positive streamers developing in mineral oil was 37.5 km/s while in natural ester it was 58.5 km/s.

In the case of negative lightning impulse voltage 3rd mode streamers appeared only in natural ester. The value of inception voltage multiplier, at which this streamer mode was noticed first time, was 2.0 V_i and was identical for both electrode gaps. Interesting fact is that propagation velocity of streamers developing in natural ester increased at 1.8 V_i and 20 mm electrode gap to 4.92 km/s but without visible changes in propagation mode. Streamers developed still as the 2nd mode but with higher velocity than for lower inception voltage multipliers. Easier way for the next step extension of streamer channel, thus easier re-ignition of the streamer in natural ester may be however possible.

The areas of appearance of distinctive streamer modes marked in the Fig. 5 are characterized obviously by the specific streamer features in the field of space shapes of streamer forms and emitted light. The shapes of the streamers recorded for the testing voltages between V_i and V_a were identical as the shapes shown in Fig. 3. They did not change in the range of mentioned testing voltage confirming that developing streamers belonged to the 2nd mode. Similarly as in the case of inception voltage, the differences between the liquids tested were not observed.

Other situation occurred in the case of light oscillograms. For the 2nd mode streamers some differences were recorded both between the liquids and between the subsequent inception voltage multipliers. Figure 6, which shows the magnified fragment of the typical waveshapes of light emitted during propagation of positive and negative streamers respectively, allows for identification these differences. An increase of the testing voltage caused the significant increase of frequency of light pulses. This took place similarly for both liquids and both voltage polarities. The pulses generated by the streamers propagating in the mineral oil were still less frequent than in the ester. In contrast to the positive streamers developing at inception voltage and at the multipliers of inception voltage equal to 1.2 and 1.4, positive streamers at higher voltages touched the insulating pressboard sheet placed on the opposite grounded electrode and spread out over this sheet in the form of surface discharges. Simultaneously, these streamers generated the so-called return channel [19, 22]. Starting from the value of testing voltage equal to 1.6 V_i, appearance of return channel finishing the propagation of positive streamers. This took place in most cases, both in natural ester and mineral oil. The mentioned return channel was clearly visible in the light courses as a wide pulse at the end of the sequence. The examples form the Fig. 6a and 6b present just such situation.

In the case of negative streamers sequence of light pulses did not end with a visible wide pulse. Thus, it may be supposed that such channel did not appear.

As was pointed out, achievement of the acceleration voltage V_a caused the change in the propagation mode of the developing streamers. This was noticed in natural ester both in the case of positive and negative LI while in mineral oil only in the case of positive LI. Figure 7 presents the examples of the typical oscillograms registered during development of the streamers at voltage level higher than acceleration voltage. In comparison to the oscillograms registered for 2nd mode streamers, this may be observed that propagation of the streamers was faster and appearance of wide light pulse at the end of the series followed after 1–2 μs.

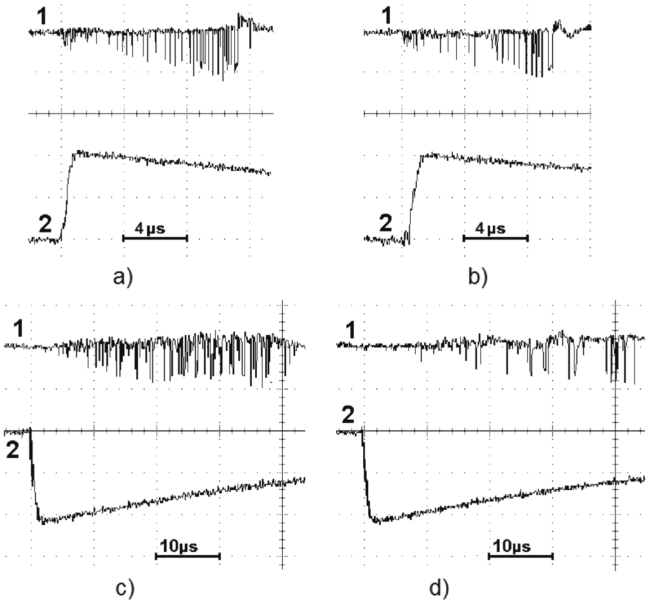

Fig. 6. Typical light oscillograms recorded during propagation of 2nd mode streamers at testing voltage $V = 104$ kV (1.6 V_i), $d = 20$ mm: a) natural ester, positive polarity, b) mineral oil, positive polarity, c) natural ester, negative polarity, d) mineral oil, negative polarity; 1 – light [arb. units], 2 – voltage [50 kV/div.]

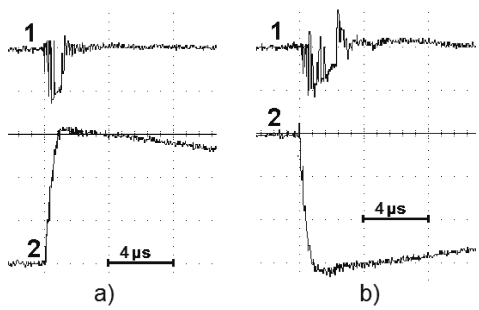

Fig. 7. Typical light oscillograms recorded during propagation of 3rd mode streamers: a) positive lightning impulse, natural ester, $V = 156$ kV (2.4 V_i), $d = 20$ mm, b) negative lightning impulse, natural ester, $V = 156$ kV (2.4 V_i), $d = 20$ mm; 1 – light [arb. units], 2 – voltage [50 kV/div.]

The registered pulse was definitely wider than in the case of development of the 2nd mode streamers which meant that phenomenon of surface discharges was more intensely and created return channel was more energetic. The large amount of light connected with this process caused the saturation of the photomultiplier (its current became positive). However, taking into account that this happened only in the final stage of the streamer development, this saturation had no influence on the interpretation of the oscillograms registered.

Unfortunately, presentation of shadowgraph photos of the 3rd mode streamers was not possible. Intensive light derived from surface discharges and return channel was so strong and it disturbed the images registered. This was because delay time of closing the camera shutter was too long and before this closing the mentioned light was caught by camera. However, it was possible to record a static photo of the streamers in the moment of touching by them the insulating sheet placed on the grounded electrode. Example of such the photo was shown in Fig. 8. This photo concerns the positive streamer in natural ester at 156 kV and 20 mm gap.

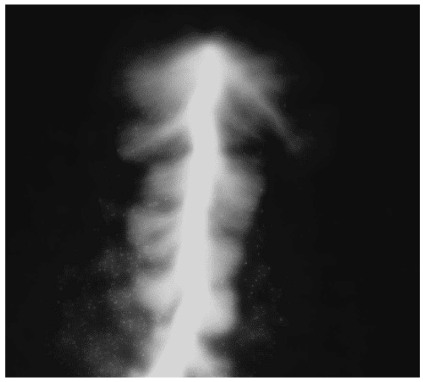

Fig. 8. Static photo of positive 3rd mode streamer in natural ester: $V = 156$ kV (2.4 V_i), $d = 20$ mm

For positive streamers developing in natural ester, both in the case of 15 and 20 mm electrode gap, breakdown events were noticed. So, this confirmed that this liquid may be more susceptible on the impact of lightning impulse and formation of breakdown channel is easier when natural ester is used as an insulating liquid. Breakdowns in ester were registered both acoustically and in the recorded voltage waveshape. Breakdown occurred for the inception voltage multiplier equal to 2.4 V_i, wherein for 15 mm gap this took place in 7 of 20 cases and for 20 mm gap in 4 of 20 cases. Estimated propagation velocity indicated that breakdown was a result of propagation of 3rd mode streamers. The observation of insulating sheet confirmed however the supposition that breakdown channel shorted the electrodes partly along the surface of the insulating presboard sheet used. This sheet was not broken. Example of oscillogram for breakdown event in 15 mm gap in natural ester was presented in Fig. 9.

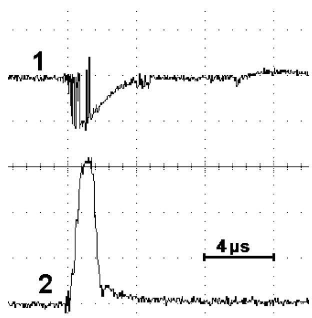

Fig. 9. Breakdown in natural ester: $V = 156$ kV (2.4 V_i), $d = 20$ mm, positive polarity; 1 – light [arb. units], 2 – voltage [50 kV/div.]

4. Conclusions

It appears from the conducted experimental studies that inception voltages of the streamers, developing respectively in natural ester and mineral oil, may be treated as the same considering the given voltage polarity and electrode gap. The difference obviously exists in the obtained parameters of Weibull distribution and in the medians calculated, but from statistical point of view this difference is not significant and conclusion on equality of inception voltages may be successfully formed. Thus, it may be supposed that mechanisms leading to streamer initiation (physical process responsible for first discharge channel formation) are similar in both the liquids tested because the same value of inception electrical field stress decides about the initiation.

The streamer characteristics obtained (spatial shapes and emitted light), registered respectively for inception voltage and inception voltage multipliers, were also noticed as a very similar considering the given propagation mode. One important difference is that the light pulses emitted by the streamer channels were more frequent and sometimes had higher peak values in all the range of testing voltages in the case of natural ester. Such conclusion must be however assessed with reserve because it does not take into account the different absorption coefficients of both the liquids tested. However, trying to explain this finding, this may be concluded that found difference resulted from easier way for the next propagation step of the streamer developing in natural ester. The charge carriers of both polarities left in the interelectrode space influence on the process of re-ignition of the streamers by influence on the value of actual electric field which depends not only on the instantaneous value of the testing voltage but also on aforementioned surface and space charge densities. If the restoration of the former electrical field stress is easier in the case of natural ester, next propagation steps occur faster than in the case of mineral oil.

The differences between both the liquids tested were also noticed in the moment of appearance of the 3rd mode streamers with an increase of testing voltage. Fast positive 3rd mode streamers appeared in natural ester at much lower testing voltage related to inception voltage (1.8 V_i) than in the case of mineral oil (2.2 V_i). In the category of absolute values of testing voltage the obtained difference was 24 and 26 kV respectively for 15 and 20 mm electrode gap. Concerning the negative streamers, within the range of applied testing voltages, 3rd mode streamers appeared only in natural ester at 2.0 of V_i and above this multiplier. This confirmed the conclusions from previously published results of the studies that natural esters have a lower ability than mineral oil to protect against appearance of fast and high energetic 3rd mode streamers [11–13]. Additional finding confirming above conclusion is that the streamers developing up to complete breakdown were observed only in natural ester. This took place at inception voltage multiplier equal to 2.4 V_i. On the other hand, even if the breakdown did not occur, the surface discharges, which appeared after reaching by streamer the insulating presboard sheet, placed on grounded electrode, left, in the case of natural ester, more visible tree-like channels on this sheet than in the case of discharges in mineral oil. Probably, the different chemical structures of both liquids give the differences which were found during the studies performed.

Because we cannot have an influence on the propagation velocity of the streamers which were already initiated in the given dielectric liquid (introduction of the barrier does not slow the 3rd mode streamer), it seems that limiting the overvoltages, when transformer is filled with natural ester, may be one of the most important issue in the insulation coordination process. Elimination of the potential reason of the appearance of the 3rd mode streamers, which may cause finally the destruction of the paper insulation, may be stated as a main aim in the overvoltage protection of ester filled power transformers.

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