Streak Observation of Dc Pre-breakdown Phenomenon in Silicone Oil/Low Density Polyethylene (LDPE) with Different Viscosities

Amir Izzani Mohamed, Ryotaro Ozaki and Kazunori Kadowaki

Abstract: We observe streak images of dc pre-breakdown in silicone-oil (10 cSt, 100 cSt and 10000 cSt) / low density polyethylene (30 μm in thickness) composite insulation under needle / sphere electrode by using the 20 meter long image guide scope and a streak camera. In the case of composite insulation with 10 cSt of silicone-oil, breakdown light propagates from the needle side under both voltage polarity. However, in the 10000 cSt case, breakdown light propagates from the film side under the negative voltage polarity. The mechanism of these transient phenomena are discussed in this paper.

Index Terms: dc breakdown, streak observation, composite insulation

1. Introduction

Every insulation form (gas, liquid or solid) possesses their own characteristic. The combination of those insulators i.e. liquid and solid can be regarded as a good idea because the liquid has ability to recover while the solid has high-voltage withstand. However, this is not applied in all cases. Narasaki previously reported that breakdown voltage V_b of liquid (oil) / solid (thin film) composite insulation (with needle–plane electrode configuration) under dc stress was lower than that in liquid only case [1]. This is believed to be the effect of space charge in breakdown process [2][3][4][5][6][7].

One of the method to study this phenomenon is by optical observation. This method can be used to study physical processes of breakdown such as initiation and propagation of streamer. However under dc stress, pre-breakdown phenomenon (breakdown light at film or at needle electrode) is difficult to be observed because it occurs extremely fast and in uncertain time during voltage application. There are very few reports on optical observation method of dc breakdown [8][9][10][11][12]. In these methods, breakdown light will pass through 2 paths; (1) light delay path and (2) photographic set triggering path. As light travels extremely fast, operating speed of photographic observation system that currently available is not sufficiently fast to photograph the initiation and development process of dc breakdown. Therefore, the breakdown light must be delayed to match processing speed of the photographic observation system. This is the reason why a light delay path is needed. By using the light delay path, an observer will have sufficient time (in our case, time is in nanosecond range) to photograph a desirable breakdown light image.

Previously, in order to understand the physics of breakdown phenomenon under dc stress, a photographic observation system for dc breakdown by using a light delay path (the 20 m long image guide scope, denoted as IGS) and high-speed-gate-adapted image intensifier [10] was developed. Intensified breakdown light image was captured by a video camera. By using this system, photograhic observation of breakdown light image on several composite insulation systems were carried out [13] [14].

In this paper, improvement of the observation system is performed. Image intensifier with high speed gate and video camera is replaced by a streak camera. In the previous system, during observing breakdown phenomenon of liquid / solid composite insulation, we were only able to capture either a pre-breakdown light image (breakdown light near electrode) or a complete breakdown light image (light bridges between the gap). By using a streak camera, transition process from pre-breakdown to complete breakdown can be observed.

Purpose of this study is to explain mechanism of breakdown (includes initiation of breakdown and complete breakdown process) in silicone oil / LDPE composite insulation with

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low and high viscosities (kinematic viscosity) in 1mm gap. In sample with low viscosity oil, it is assumed that breakdown will initiate at needle tip. While in sample with high viscosity oil, breakdown will initiate at film. This is because breakdown voltage of high viscosity oil is considerably higher than that with low viscosity. Joule heating due to high current density at needle tip assist the production of microbubbles in low density case. Breakdown can easily initiates in the bubbles (because it contains gases and V_b of gases is much lower than that of liquid). On the other hand, in high viscosity oil, all charges will accumulate on film surface because breakdown do no occur in oil. When electric field at the film is enhanced to a critical value for breakdown initiation, breakdown will occur.

2. Experimental Method

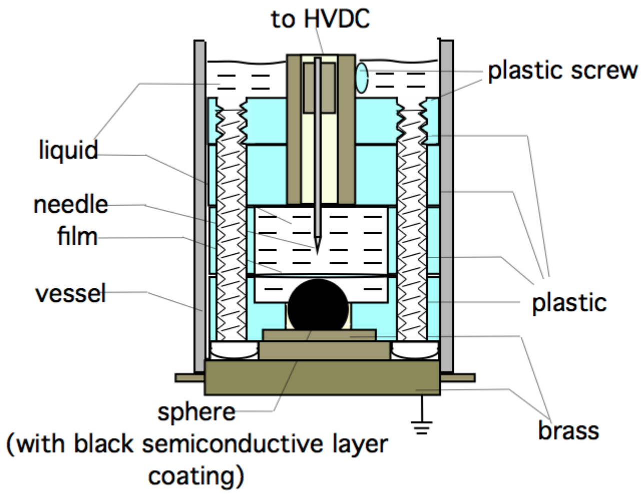


Figure 1. Sample cell

Figure 1 shows sectional view of sample cell, which is used in this study. A needle and a stainless steel sphere (10mm in diameter) is used as high voltage electrode and ground electrode respectively. The needle tip is maintained at 10µm tip of radius by electrolytic etching in highly-concentrated sulphuric acid solution. The process is repeated everytime before each experiment. The sphere ground-electrode is laminated with epoxy-based carbon black semiconduction layer (namely DOTITE) in order to omit the influence of reflection on its' surface during breakdown. Low-density polyethyelene (LDPE) with 30 µm in thickness (Japan Polychem LF440HB) and silicone Oil (MOMENTIVE Performance Material Inc.) with viscosity of 10 cSt (TSF451-10), 100 cSt (TSF451-100) and 10000 cSt (TSF451-1M) are used as samples. The LDPE film is soaked in etanol solution by using ultrasonic cleaner to remove dirts before placing it on the sphere electrode. Later silicone oil is poured into the surrounding space within the vessel (PMMA cylinder). The sample cell is degassed prior to the experiment in order to remove voids in the oil.

Figure 2 shows a working time chart of the streak observation system. The meaning of each notation is stated below the chart. The observation system is shown in figure 3 and is introduced in detail in our previous paper [15]. Once breakdown occurs, breakdown light will pass through 2 path; (1) IGS (Mitsubishi Cables Ltd. RBD45-A2008) and (2) streak camera (Optronis GmBh, SC-10, 2 ps time resolution, <100 µm spatial resolution) triggering system. The breakdown light image is delayed for 100 ns (travelling speed inside IGS is 2.0×10^8 m/s) in the IGS. In path (2), breakdown light will be detected by a photomultiplier 2 (Hamamatsu Photonic H5783-03) via an optical fibre cable. Then the produced electrical signal is transferred to pulse generator. The pulse generator will generate a TTL level pulse which is used to trigger the streak camera.

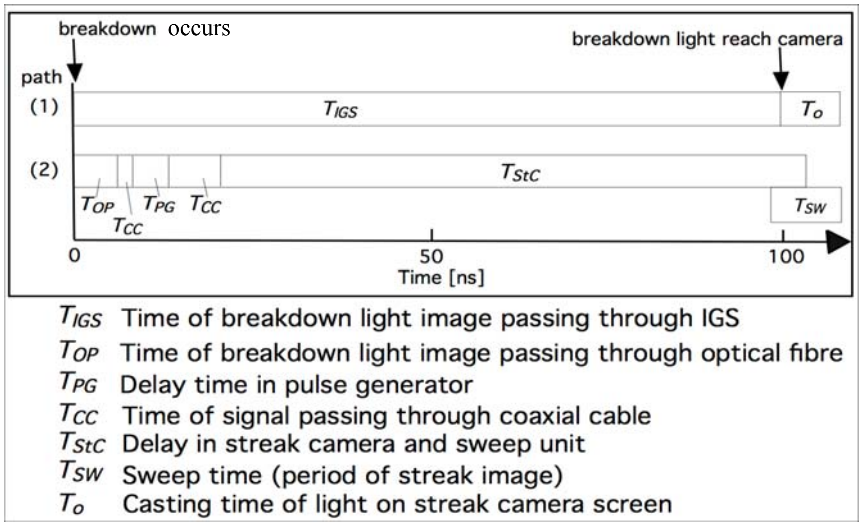


Figure 2. Timing chart

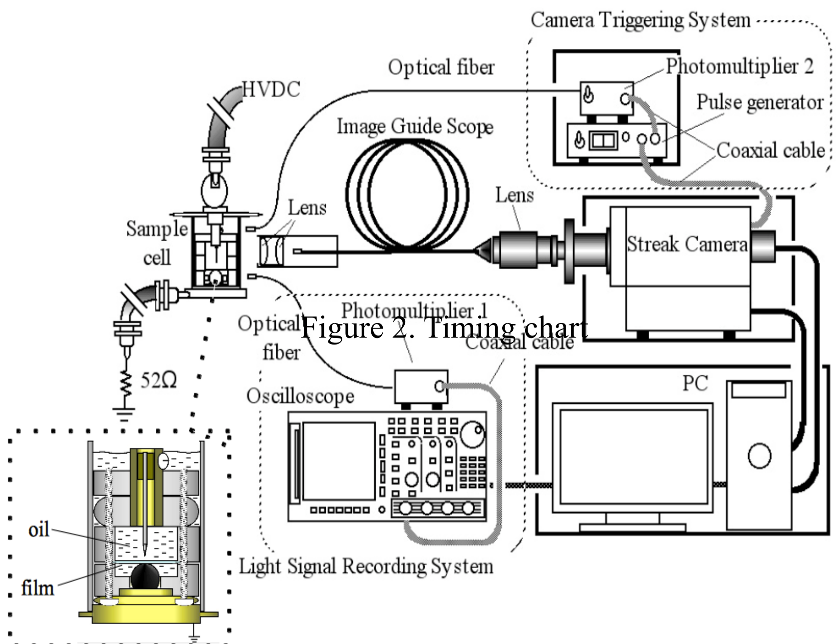


Figure 3. Illustration of experimental arrangement diagram

The arrival time of breakdown light image to the camera (which is 100 ns after breakdown by travelling through the IGS) and the time of camera triggering signal should be syncronized in order to capture a desirable streak image. The streak camera sweep speed is set to 500 ps/mm so that a streak image with duration of 10 ns can be obtained (phosphor screen size inside the streak camera is 20 mm).. In this experiment, electrode is configured in such a way to ensure that electric field between the needle tip (high voltage electrode) and the sphere (ground electrode) right below the needle is very strong so that breakdown can be induced mostly there. This is to ensure that the breakdown light will properly enter a very-narrow-slit of streak camera (200 μm).

Experimental procedure is explained as follows. Ramp voltage (0.1 kV/s) is applied until breakdown occurs. Dc high voltage source with negative and positive polarity are used. Number of sample in each experimental conditions is 5. Breakdown light signal as well as streak image are recorded in a personal computer placed in faraday cage. The streak data is analyzed by using Optoanalyse software provides by Optronis GmBh.

3. Results and Discussion

A. Breakdown voltage and streak images

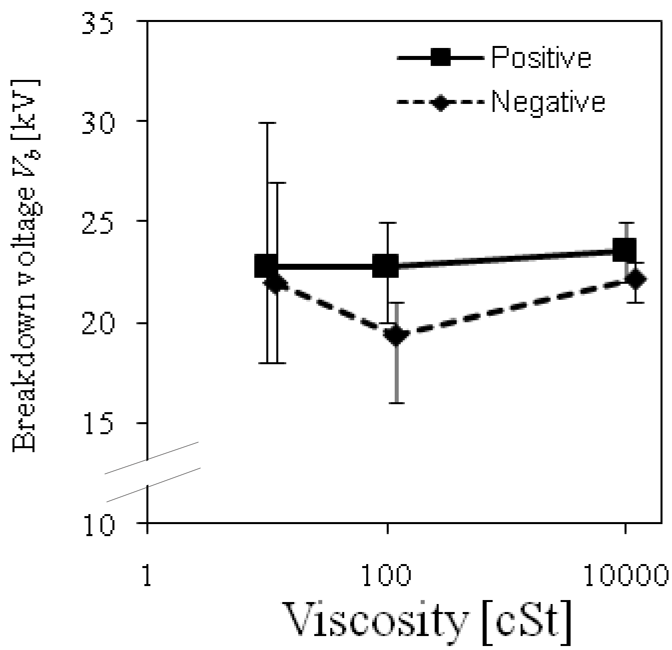
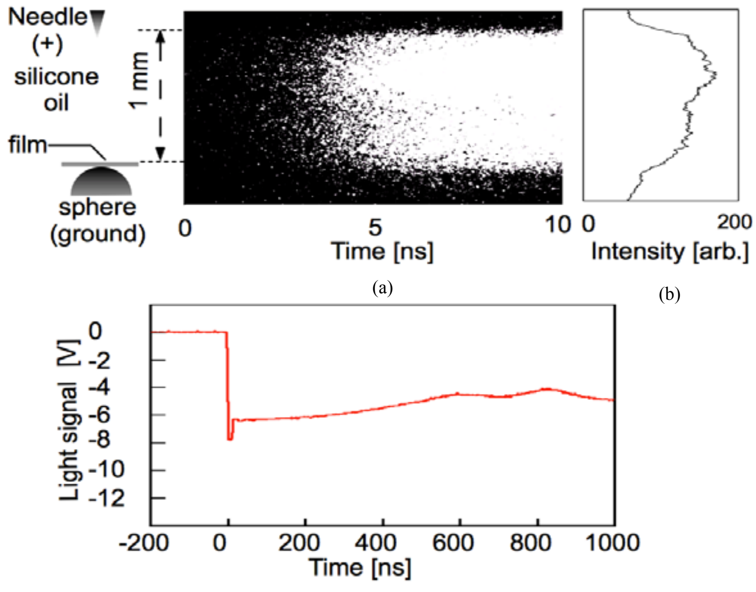


Figure 4. Relationship between breakdown voltage V_b of composite insulation and viscosity of silicone oil used in the composite.

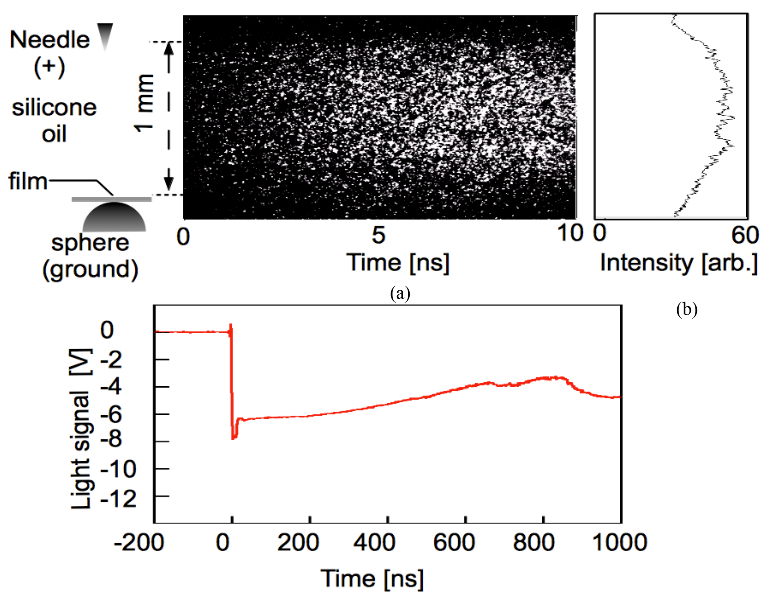
Figure 4 shows relationship between breakdown voltage V_b of the composite insulation and Viscosity of silicone oil used in composite insulation. From figure 4 it is understood that breakdown voltage of composite insulation under positive polarity voltage application is higher than that under negative one. For 10 cSt case, V_b scatters widely under both polarity voltage application. While in 100 cSt case, the scatter of V_b decreased. The error bar indicates that scattering of V_b decreases further in the case of 10000 cSt. The decrease in scattering of V_b with the increase of silicone oil viscosity can be translated into variation in breakdown mechanism in composite insulation with different viscosities. When the voltage application is increased, current density at the needle tip also increases significantly. Joule heating that is induced during this time may produce microbubbles at needle tip vicinity. In low viscosity case, microbubble can be 'grown' due to instability of electrohydrodynamic (EHD) along with the presence of joule heating produced at the high current density region. Therefore it can be assumed that breakdown initiates in the microbubble. This will trigger complete breakdown of the composite insulation afterwards. On contrary, as there is almost no EHD in high viscosity liquid, microbubbles is not produced during voltage application. This consequently will reduce the probability of breakdown initiation by microbubbles at needle tip region. Therefore, in very high viscosity case (10000 cSt), initiation of breakdown at needle idea can be eliminated thus leaving only the idea of breakdown initiation at film. At this point, the assumption stated earlier in the introduction is still agreeable.

However, in most cases in this experiment, information from the obtained streak images are not totally in agreement with our assumption. In the case of 10000 cSt, under both negative and positive polarities, breakdown sometimes occurs at needle electrode. On the other hand, in most cases of 10 cSt, breakdown initiates from tip of the needle. Breakdown initiation at film was not observed in 10 cSt case under both polarity. Figures 5, 6 and 8 show streak images that agree with our assumption.



(c)

Figure 5. (a) Streak image, (b)integrated intensity distribution profile and (c) breakdown light signal for silicon oil (10cSt)/LDPE sample under positive stress.



(c)

Figure 6. (a) Streak image, (b) integrated intensity distribution profile and (c) breakdown light signal for silicon oil (10000cSt)/LDPE sample under positive stress.

Figure 5(a) shows streak image, (b) integrated intensity distribution profile and (c) breakdown light signal of silicone oil (10 cSt)/LDPE composite insulation under positive polarity voltage application. From the streak image alone, it is unclear where the initiation of breakdown position is. By referring to figure 5 (b) it can be said that breakdown is initiated at needle tip as the integrated intensity is higher at that particular position than the others. Therefore, in this case, it can be postulated that positive streamer propagates from needle tip towards the counter electrode causing complete breakdown. It is difficult to determine the streamer propagation speed from the streak image alone as the slope of the breakdown light image (from initiation at the needle tip to finishing at the ground electrode) is almost unseen. By rough calculation, as the streamer took at most 1ns to propagate across the 1 mm gap, calculated streamer velocity is at least 1000 km/s. This streamer velocity is extremely fast as compares to other reports [16][17][18][19]. Figure 5 (c) shows that there is no other event than complete breakdown.

Figure 6(a) streak image, (b) integrated intensity distribution profile and (c) breakdown light signal for silicone oil (10000 cSt) / LDPE sample under positive stress. Streak image of silicone oil (10000 cSt) / LDPE composite insulation under positive polarity voltage application is very similar to that in figure 5. This figure shows contradiction to our assumption. This shows that high field at the needle is a stronger factor than high-viscosity-oil factor under positive voltage application in initiating breakdown. Even in 10000 cSt case, positive streamer is easily formed and instantly cause complete breakdown.

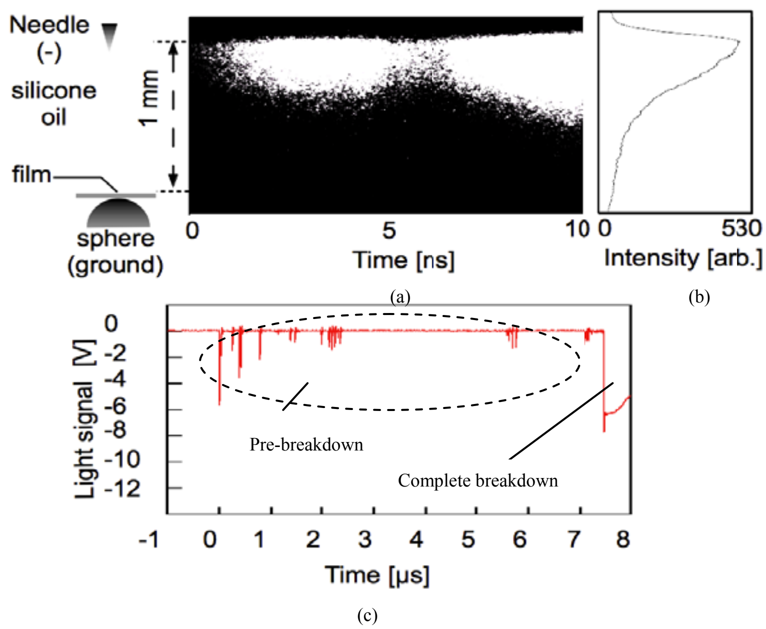


Figure 7. (a) Streak image, (b) integrated intensity distribution profile and (c) breakdown light signal for silicon oil (10 cSt)/LDPE sample under negative stress.

Figure 7(a) shows streak image, (b) integrated intensity distribution profile and (c) breakdown light signal of silicone oil (10 cSt)/LDPE composite insulation under negative polarity voltage application. From the streak image, it is understood that breakdown initiates at needle tip but does not instantly trigger complete breakdown. It takes 7.5 µs to trigger complete breakdown as shown in figure 7(c). The light signal during this time is that of negative streamer which intermittently occurs at the needle. This is considered by the fact that propagation ability of negative stremer is lower than positive streamer. Therefore, complete breakdown do not occur instantly as such in positive needle case (refer figure 5). It is assumed that negative streamer supply negative charges and accumulate on the film surface. Upon reaching critical field at the film, film breakdown occur with successive positive streamer propagation from ground electrode causing complete breakdown of the composite insulation. However, streak image of complete breakdown is not obtained in this study.

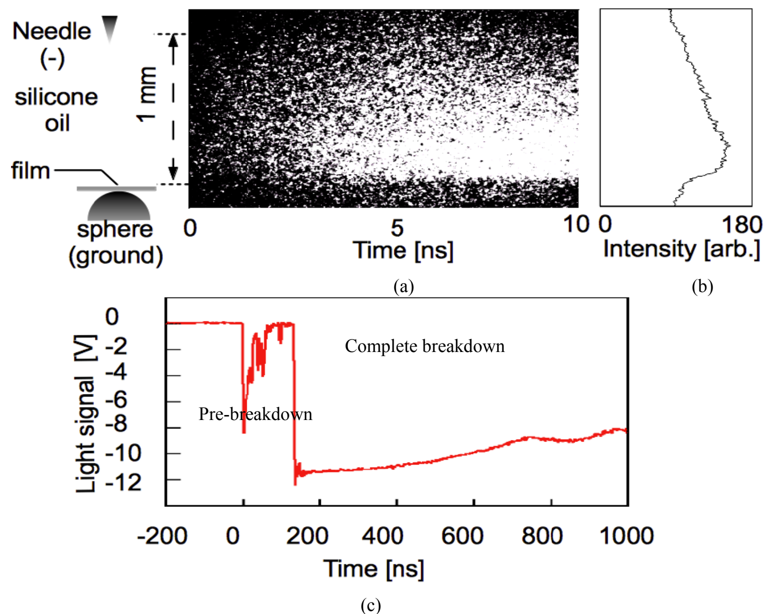


Figure 8. (a) Streak image, (b) integrated intensity distribution profile and (c) breakdown light signal for silicon oil (10000 cSt)/LDPE sample under negative stress.

Figure 8 (a) shows streak image, (b) integrated intensity distribution profile and (c) breakdown light signal of silicone oil (10000 cSt) / LDPE composite insulation under negative polarity voltage application. From figure 6 (c) pre-breakdown light signal of film breakdown was recorded. This type of pre-breakdown light signal was only observed under negative polarity voltage but not in positive polarity. From the figure, complete breakdown of the composite insulation occurs after 155 ns. Therefore, it can be said that the obtained streak image belongs to film breakdown. This phenomenon can be explained as follows. Charges from needle tip travel to counter electrode and accumulate on film surface right below the needle tip and then create negative charges channel between film surface and the needle with continous charges injection from the needle. Upon reaching critical field strength, film breakdown occurs. The negative charges channel is also absorbed into ground electrode. After that, successive negative charges are injected again into the bulk of oil towards ground electrode along with the injection of positive charges from the ground electrode. The high electric field in oil's bulk then induced positive streamer. The streamer propagates from ground electrode towards the needle thus causing complete breakdown of the composite insulation [22][23].

Conclusions of breakdown initiation location and breakdown time lag from pre-breakdown to complete breakdown in each experimental condition are shown in table 1, for negative polarity and table 2, for positive polarity. From these tables it can be postulated that in most cases, breakdown initiates at needle electrode regardless of the viscosity and polarity of the voltage. Pre-breakdown signals were only observed under negative needle cases in some cases (at least 2 cases out of 5).

Table 1. Mean time lag from pre-breakdown to complete breakdown and breakdown initiation position under negative polarity voltage application

	Viscosity [cSt]		
	10	100	10000
Mean time lag	9.5µs	0	155ns
Initiation position	Needle tip or oil	Needle tip or oil	Film or needle tip

Table 2. Mean Time Lag From Pre-Breakdown To Complete Breakdown And Breakdown Initiation Position Under Positive Polarity Voltage Application

	Viscosity [cSt]		
	10	100	10000
Mean time lag	0	0	0
Initiation position	Needle tip or oil	Needle tip or oil	Needle tip or oil

B. Difference of streamer propagation capabilities between both polarities.

In gas discharge with positive needle, as ionization coefficient increases with the increase in applied voltage, electron avalanche will takes place. Electron avalanche is consisted of head (electron swarm) and tail (positive ions swarm). The electron will be absorbed into the positive needle and the positive ions swarm attempting to move to cathode. This propagation of positive ions swarm will enhance electric field between the ions and the cathode. This will induce another avalanches. This discharge states is called positive streamer. Positive streamer will occur prior to complete breakdown across the gap. This type of streamer can easily propagate to bridge both electrodes [20][21]. In this experiment, we observed similar type of streamer as such in figure 5 and 6 even our dielectric medium is oil.

In negative needle case, electric field at needle tip is also enhanced with the increase in applied voltage. This will also increase ionization coefficient at the needle tip and yields a great number of electrons. After that, positive ions and another electrons are also produced by collision ionization causing electron avalanche to occur. The generated electrons swarms attempt to propagate to counter electrode (anode). However, repulsion forces between each of them are generated because the number of electron is huge. This phenomenon seems like increasing radius of the needle, which consequently reduces the electric field between the electrons swarm and the anode. Therefore, further increase in applied voltage is needed in order to cause breakdown. This will cause delay in breakdown under negative needle. This discharge state is called negative streamer [20][21]. Similar phenomenon can be seen in figure 7 even our dielectric medium is oil.

4. Conclusion

This study can be concluded as follows:

1. Positive polarity - regardless of oil's viscosity, positive streamer propagation in oil layer was followed by complete breakdown. The time lag from the streamer initiation to the complete breakdown was extremely short. This fact indicated that ionization caused by the streamer in oil spontaneously occurred and then the positive streamer immediately penetrated into LDPE layer.
2. Negative streamer – negative streamer from needle tip propagated at the initial stage of pre-breakdown for the case of the low-viscosity oil. The negative streamer intermittently propagates in the oil and eventually induces complete breakdown. The time lag was very

long because propagation capability of the negative streamer in oil is low. However, the time lag becomes short with increasing in the oil viscosity. One of the reason for the decrease in time lag was that film breakdown was caused by field distortion due to charge accumulation on the film surface at the initial stage of pre-breakdown. Since the propagation capability of positive streamer from film breakdown spot towards the negative needle must be very high, the time lag became short.

5. Acknowledgement

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References

[1] N. Narasaki, K. Kudo, and Y. Nitta, "Direct Voltage Breakdown of Silicone oil/PET Film Composite with Needle/Plane Electrode System", *IEEE Trans. Dielectr. and Electr. Insul,* EI-19, Vol. 4, pp. 354-358, 1984.

[2] J. H. Mason, "Breakdown of Solid Dielectric in Divergent Fields," *Proc. of the IEE - Part C: Monographs*, Vol. 102, no. 2, pp. 254–263, 1955.

[3] J. Artbauer and J. Griac, "Intrinsic Electric Strength of Polyethylene in the High-temperature Region," *Proc. IEE*, Vol. 112, p. 818, 1965.

[4] R. Cooper, C. H. Rowson, and D. B. Watson, "Intrinsic Electric Strength of Polyethylene," *Nature*, Vol. 197, pp. 663–664, 1963.

[5] R. Fava, "Intrinsic Electric Strength and Electromechanical Breakdown in Polyethylene," *Proc. IEE*, Vol. 112, pp. 819–823, 1965.

[6] A. Bradwell, R. Cooper, and B. Varlow, "Conduction in Polyethylene with Strong Fields and the Effect of Prestressing on the Electric Strength," *Proc. IEE*, Vol. 118, pp. 247–254, 1971.

[7] D. B. Watson, "The Electric Strength of Perspex as a Function of Voltage Rise Time," *J. Phys. D: Appl. Phys.*, Vol. 5, pp. 410–414, 1972.

[8] F.G. Dunnington, "The Electrooptical Shutter –Its Theory and Technique-", *Phys. Rev.*, Vol.38, pp. 1506-1534, 1931.

[9] F.G. Dunnington, "An Optical Study of Formation Stages of Spark Breakdown", *Phys. Rev.*, Vol.38 pp. 1535-1548, 1931.

[10] R. Cooper and C.T. Elliot, "Formative Processes in the Electric Breakdown of Potassium Bromide", *Brit. J. Appl. Phys*, Vol.17, pp. 481-489, 1966.

[11] D.W. Auckland R. Cooper and J. Sanghera, "Photographic Investigation of Formative Stage of the Electric Breakdown in Diverging Field", *IEE Proc.*, Vol.128, No. 3, pp. 481-489, 1981.

[12] K.Kadowaki, S.Arikawa, S.Nishimoto and I.Kitani, "Photographic Observation System for DC Prebreakdown Phenomena in Dielectrics using the Long Image Guide Scope", *Jpn. J. Appl. Phys.*, Vol.36, No.12A, pp. 7289-7290, 1997.

[13] K. Kadowaki, K.Kuwabara, S.Nishimoto and I.Kitani, "Dc Prebreakdown Light in Silicone oil/Polymer-film Composite with Sphere-sphere Electrodes," *Proceeding of the International Symposium on Electrical Insulating Materials*, pp. 876-879, 2001.

[14] K. Kadowaki, S. Kawakami, S. Nishimoto and I. Kitani, "Prebreakdown Light in Glass-plate/Polymer-film Composite Subjected to Dc Ramped Voltages," *Proceeding of the International Symposium on Electrical Insulating Materials*, pp. 297-300, 2005.

[15] A. I. Mohamed and K.Kadowaki, "Streak Observation System for DC Pre-breakdown Using an Image Guide Scope", *Jpn. J. Appl. Phys.*, Vol.36, No.12A, pp. 7289-7290, 1997.

[16] W. G. Chadband, "On Variations in the Propagation of Positive Discharges between Transformer Oil and Silicone Fluids", *J. Phys. D Appl. Phys.*, Vol. 13, pp.1299-1307, 1980.

[17] J. C. Devins, S. J. Rzad and R. J. Schwabe, "Breakdown and Prebreakdown Phenomena in Liquids", *J. Appl. Phys.*, Vol. 52, No. 7, pp.4531-4545, 1981.
[18] P. Rain and O. Lesaint,"Prebreakdown Phenomena in Mineral Oil under Step and ac Voltage in Large-gap Divergent Fields", *IEEE Trans. Diel. and Insul. Elec.*, Vol. 1, No. 4, pp.692-701, 1994.
[19] C. T. Duy, O. Lesaint, A. Denat and N. Bonifaci,"Streamer Propagation and Breakdown in Natural Ester at High Voltage", *IEEE Trans. Dielectr. and Electr. Insul. Elec.*, Vol. 16, No. 6, 2009, pp.1582-1594.
[20] K. Tatsuo, K. Teruya and Y. Satoru, "High Voltage Engineering", Denki Gakkai Daigaku Kouza, 3rd Revised Edition, IEEJ, 2003. (in Japanese)
[21] K. Kadowaki, "Dc Pre-breakdown Phenomenon in Liquid / Solid Composite Dielectric", Doctor of Engineering Dissertation, Ehime University, 2002. (in Japanese)
[22] I. Kitani, K. Kadowaki and K. Arii, "Transition Process from Film Breakdown to Complete Breakdown in Silicone-Oil / Polymer-Film Composite under Point-Cathode / Plane-Anode", *Jpn. J. Appl. Phys.*, Vol. 28, No. 12, pp.2532-2536, 1989.
[23] I. Kitani, K. Kadowaki and K. Arii, "DC Breakdown Voltage in Silicone-Oil / Polymer-Film Composite", *Proc. Of 3rd Int. Conf. on Properties and Applications of Dielectric Materials*, pp. 1181-1184, 1991.

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