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DETECTION AND RECORDING OF PARTIAL DISCHARGES BELOW THE INCEPTION VOLTAGE WITH A POINT–PLANE ELECTRODE ARRANGEMENT IN AIR: EXPERIMENTAL DATA AND DEFINITIONS

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The problem of insulation damage from partial discharges below the inception voltage has not yet attracted much attention. Indications of possible damage exist from previous research. In this paper, the possibility of existence of such phenomena is investigated with small air gaps and point-plane electrode arrangements. It is shown that random discharges below inception voltage may exist. Such discharges are registered and their waveforms are discussed. Experimental evidence is offered that discharges change from the pulse-type to a pulseless-type as the air gap becomes larger. Phenomena affecting in some way the insulating systems below inception may help us to better understand the mechanism of small current flow at relatively low voltages and may contribute to a better formulation of dielectric materials. Furthermore, besides the experimental results, the problem of definitions regarding these phenomena is discussed and commented upon.

Keywords: partial discharges, inception voltage, gap spacing, charging events below inception voltage

1 INTRODUCTION

The questions regarding insulation because of partial discharges (PD), PD detection and mechanisms of PD have been dealt with before [1]. What has not yet been researched extensively, is the problem of deterioration of insulating materials below inception voltage. Some work has been carried out in the nineties by Bruning and his team [2]. In the latter work, it was indicated that the type of byproducts appearing at or above inception voltage are qualitatively the same with the byproducts below inception. It was indicated that below inception, there is a current causing polymer cavity surface chemical changes that are similar to those that occur when the polymer insulation fails at or above inception because of PD. The implications of paper [2] were significant, in that they explained to a certain extent sudden failures of insulating systems [3] — even though these systems had passed the prescribed tests — and also in that the said paper could point out to the direction of improving polymer formulation and, moreover, to a different approach to ageing insulation models [4]. Recent work performed with small air gaps and point-plane electrode arrangements, confirmed that random discharges may occur below inception electric fields [5, 6].

It is the aim of the present paper to further elaborate the above mentioned concepts and to see whether the conclusions offered in [5, 6] are valid also with different point electrode diameters. Since we claim that partial discharges are measured even below the inception voltage, a discussion will follow in the context of the present paper, as to whether the term "partial discharges" below inception voltage is appropriate or whether other terms, such as "charging phenomena" or "ionization phenomena" have to be employed.

2 EXPERIMENTAL ARRANGEMENT AND PROCEDURE

In this paper, a small Greinacher generator was used [5, 6]. The generator produces invariably 7.5 kV. This is applied to a needle-plane electrode arrangement. The needle has diameters 0.25 mm, 0.35 mm and 0.45 mm. The discharges were detected with the aid of an R-C circuit ($R = 150\,\mathrm{k}\Omega$, $C = 39\,\mu\mathrm{F}$). The discharges were observed on the screen of a Tektronix oscilloscope (type 7623 A, bandwidth 20 MHz). The distance between the electrodes is measured with the aid of feeler gauges.

For all three electrode arrangements used, the air discharges were first recorded at a certain distance, which was the air gap where the inception voltage was 7.5 kV. This distance is named critical air gap. At this gap continuous discharges could be recorded. Bearing in mind that the Greinacher generator produced only a fixed voltage of 7.5 kV, the air gap was varied (*ie* it was made larger) in order to see whether discharges would also occur. It would be helpful if we can clarify here some definitions and notions: conventionally, inception voltage is the voltage at which discharges are detected. At and/or above this level, discharges are considered harmful for the insulating system. Discharges at and/or above this voltage level will have a detrimental effect on ageing in the long run. Our aim is to look for discharges which are sporadic,

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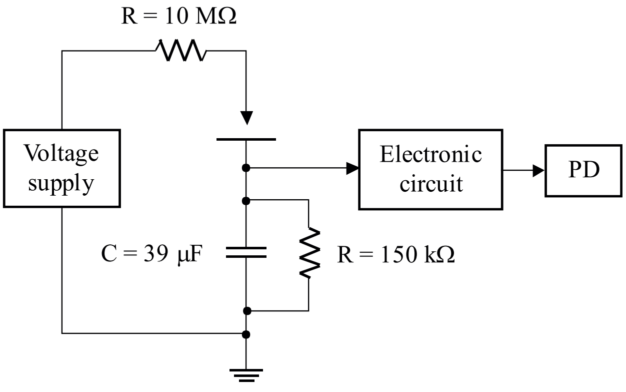

Fig. 1. Experimental arrangement used. By "Electronic circuit" is meant the detecting and counting circuit incorporating a programmable micro-controller which transferred the number of recorded pulses to the PC (personal computer which is symbolized by PD

Table 1. Results for the needle diameter of 0.25 mm

Air Gap (mm)	Experimental duration	Number of PD	E_{avg} (kV/mm)	$E_{\max}$ (kV/mm)
0.7	45 sec	14767	10.714	38.062
0.75	30 sec	8977	10	37.280
0.8	25 sec	5996	9.375	36.575
0.85	20 sec	5359	8.824	35.935
0.9	5 min	336	8.333	35.351
0.9	10 min	9723	8.333	35.351
0.9	15 min	0	8.333	35.351
0.9	20 min	17629	8.333	35.351
0.95	10 min	2	7.895	34.815
0.95	10 min	959	7.895	34.815
0.95	20 min	0	7.895	34.815
0.95	20 min	386	7.895	34.815
0.95	60 min	4	7.895	34.815
1	30 min	0	7.5	34.320
1	55 min	0	7.5	34.320
1.05	35 min	0	7.143	33.861
1.05	60 min	0	7.143	33.861

Table 2. Results for the needle diameter of 0.35 mm

Air Gap (mm)	Experimental duration	Number of PD	E_{avg} (kV/mm)	$E_{\max}$ (kV/mm)
0.7	40 sec	8415	10.714	33.253
0.8	15 sec	2633	9.375	28.964
1	10 sec	1509	7.500	27.021
1.2	10 sec	1133	6.250	25.606
1.3	10 sec	297	5.769	25.028
1.4	10 sec	297	5.357	24.514
1.45	15 min	163	5.172	24.278
1.5	10 min	0	5	24.054
1.5	10 min	16	5	24.054
1.5	30 min	2	5	24.054
1.5	35 min	0	5	24.054
1.55	60 min	0	4.839	23.840

are generally of small magnitude, do not necessarily cause ageing or insulation damage, but which may develop in the long term into dangerous discharges. In the context of this work, and because a fixed voltage was used, instead of varying the voltage, we varied the gap spacing. It goes without say that if random, sporadic discharges were taking place at larger air gaps, *ie* larger than the critical gap, this would be equivalent to the assumption that random, sporadic PD events would also happen — using the classical terminology — below the inception voltage.

3 EXPERIMENTAL DATA

The maximum electric field developed at the tip of the needle is given by the well known Masons formula [7]

$$E_{\max} = \frac{2dE_{\text{avg}}}{r\,ln(1+4\frac{d}{r})} \tag{1}$$

where, $E_{\max}$ is the field at the needle tip, E_{avg} is the average electric field applied to the gap ($= V/d$, where V is the applied voltage), d is the electrode gap spacing and r is the radius of the needle tip. The registration of PD was performed with a detecting and counting electronic circuit which incorporated a programmable micro-controller. The latter is programmed in order to register and to add PD pulses, which are applied at its input, *ie* PD which occur in the air gap. The micro-controller, with an appropriate software program, communicates the PD information to a personal computer and the results appear on its screen.

The smallest pulse duration, experimentally found, was $12\,\mu$s. The control of pulses was performed every $10\,\mu$s and, consequently, there was sufficient time for the elaboration of each PD pulse by the micro-controller [5, 6]. In Fig. 1, the whole experimental set-up can be seen. The resistor of 10 MΩ had a role of restricting damage because of the PD.

The resulting applied voltage was 7.5 kV and it was of negative polarity. The experimental method consisted of defining at first the gap spacing at which PD regularly appeared on the screen of the oscilloscope. This gap gave the inception field. Then we increased the gap and we observed whether PD still appeared and whether they were of intermittent nature. The method was the same for all three different diameters of 0.25 mm, 0.35 mm and 0.45 mm. Tables 1–3 give the results of the performed experiments for the three needle electrode diameters. It is evident from these Tables that as the gap spacing increases, discharges become more and more rare and sporadic.

4 DISCUSSION

From the experimental results it is observed that in all three needles, with the increase of the air gap the frequency of appearance as well as the magnitude of the PD

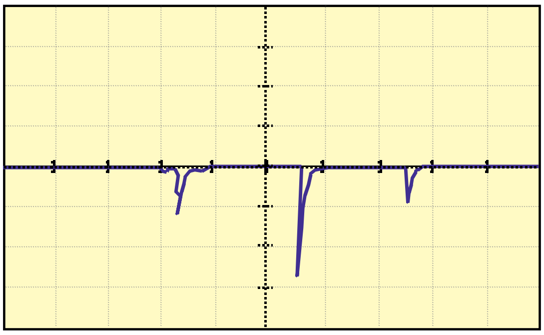

Fig. 2. Indicative PD, with an air gap of 2.05 mm and needle diameter of 0.60 mm, which was registered after a test period of 40 min (20 V/Div, 500 μs/Div). The shape of the recorded PD suggests a pulse type of mechanis

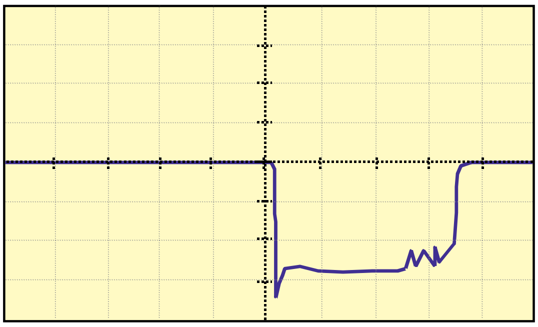

Fig. 3. Indicative PD, with an air gap of 2.10 mm and a needle diameter of 0.60 mm, which was registered after a test period of 54 min (20 V/Div, 2 ms/Div). The shape of PD suggests a pulseless type of mechanism

Table 3. Results for the needle diameter of 0.45 mm

Air Gap (mm)	Experimental duration	Number of PD	$E_{\rm avg}$ (kV/mm)	$E_{\rm max}$ (kV/mm)
0.7	15 sec	2401	10.714	25.655
0.75	20 sec	2795	10	25.038
0.8	25 sec	3418	9.375	24.485
0.9	35 sec	2503	8.333	23.530
1	20 sec	2143	7.5	22.732
1.05	20 sec	1548	7.143	22.379
1.10	20 sec	2321	6.818	22.052
1.20	15 sec	1564	6.25	21.463
1.30	35 sec	1549	5.769	20.947
1.40	15 sec	1373	5.357	20.489
1.50	15 sec	975	5	20.079
1.50	20 min	53	5	20.079
1.55	30 min	0	4.839	19.890
1.55	25 min	152	4.839	19.890
1.60	60 min	0	4.688	19.709
1.60	20 min	97	4.688	19.709
1.65	15 min	191	4.545	19.537
1.65	30 min	1628	4.545	19.537
1.70	20 min	0	4.412	19.373
1.70	30 min	0	4.412	19.373

decreases, whereas the pulse duration increases. The decrease of the magnitude of the PD can be detected from the pulse waveforms on the oscilloscope screen and from the pulse width which is recorded by the electronic circuit. Tables 4–6 show indicative values of pulse height and of pulse duration of the recorded PD as the air gap varies. A comparison of the present results with those of previous publications [5, 6] points out to the fact that there is a qualitative agreement between the results. An increase of the air gap implies an increase of pulse duration and the pulse waveform becomes more widened. In other words, the sharp waveform observed with the smaller air gaps, changes into a more widened waveform in larger air gaps. The PD pulse height decreases as the air gap increases, *ie* the PD magnitude decreases with increasing the air gap meaning that with larger gaps there are smaller PD pulses. As the gap gets larger, the applied electrical field (both average and maximum) decreases. A change in PD mechanism is bound to happen. This may suggest a change in PD mechanism, presumably from a pulse-type mechanism to a pulseless mechanism. As the air gap becomes larger, and provided that the applied voltage remains the same, the PD gets weaker and its mechanism changes.

In Figs. 2 and 3, the aforementioned change in discharge waveform is shown. The waveforms were recorded with a digital Tektronix oscilloscope type TDS 224 of a bandwidth 100 MHz. The observed discharges are shown in real time on the screen of a computer with the aid of appropriate software (Wavestar). The results registered are with a needle diameter of 0.60 mm and gap spacings of 2.05 mm and 2.10 mm. It is evident that Fig. 3 seems to indicate a pulseless discharge whereas Fig. 2 suggests a pulsive discharge. A transition seems to be at work between the two gap spacings of 2.05 mm and 2.10 mm.

For the needle diameter of 0.25 mm and for air gaps smaller than 0.9 mm, continuous PD are observed (Tab.1). For air gaps greater than 0.9 mm, random PD are observed whereas their number decreases. Obviously, the 0.9 mm air gap is the critical gap above which the PD events are rendered random. The critical gap is equivalent to the inception voltage of Bruning's papers.

For the other two needle diameters of 0.35 mm and 0.45 mm, the critical gaps are 1.45 mm and 1.50 mm respectively (Tabs. 2 and 3 respectively). The phenomena which are observed with these needle diameters are similar to those observed with the 0.25 mm needle. It seems obvious from the measurements that the increase of needle diameter has as a result the increase of the critical air gap. Needless to say that for all three needles, a decrease of the average value of the applied electrical field and of the maximum applied electrical field were observed, as the diameter of the needle became larger. It is to be noted that with the term "critical gap" we mean the air gap at which there is a transition from the many recorded PD to the very few sporadic PD.

In all three investigated needle diameters, it was noted that random PD occurred in air gaps greater than the critical air gap. In their majority, the registered PD were small in magnitude. Thus, we have indications that there are PD even above the critical gap, *ie* even below the inception voltage (or stress), if we are to use the classical terminology.

Table 4. Indicative results with needle diameter of 0.25 mm (1 V/Div, 5 msec/Div)

Air Gap (mm)	Pulse height (V)	Pulse duration (msec)
0.9	1.5	3
0.6	2.5	2
0.3	3.5	1

The results of the present study agree with the results of previous publications carried out in our laboratory [5, 6, 8]. Taking into account the results of the present paper as well as those of previous publications [5, 6], it is evident that the critical gap increases with the needle diameter.

Table 5. Indicative results with needle diameter of 0.35 mm (1 V/Div, 5 msec/Div))

Air Gap (mm)	Pulse height (V)	Pulse duration (msec)
1.45	2	2
1	3.5	1
0.5	3.5	1

Whereas Bruning and colleagues indicated that there are byproducts at and/or above inception voltage similar to those detected below it [2, 3], the present study validates their claims by presenting some indications of PD events even above the critical air gap.

Table 6. Indicative results with needle diameter of 0.45 mm (1 V/Div, 20 msec/Div)

Air Gap (mm)	Pulse height (V)	Pulse duration (msec)
1.5	1.5	3
1	3	2
0.6	3.5	1

The data of the present paper shows that PD phenomena may take place even below inception voltage or, in our case, even above the critical air gap. In that we have confirmation of the claims by Reynders, who, performing research on polyethylene samples with well defined cavities, showed that there are occasions where failure of insulation may follow after many hundreds of hours of relative PD inactivity [9]. Although a transparent gel was formed in sealed cavities and after some time formed an effective seal to the ingress of air, there was a sudden resurgence in PD activity followed by breakdown. This points out to the fact that events leading to ultimate polythene failure might have gone undetected.

Substantial support of the present paper data, can be found also in Tanaka's work [10]. He also reported the existence of very small PD, the swarming pulsive micro- discharges, which may eventually lead to breakdown. Damage because of very small PD was reported in [10] with epoxy resin samples. Such small PD were detected, however, with sensitive photomultipliers and not by conventional means. Tanaka defined such PD as swarming pulsive micro-discharges. The pulsive nature of the detected PD is evident also in our work. Our data deviates from those of Tanaka's in that, for very small partial discharges, we register pulseless discharges. This may be due to the fact that, although Tanaka researched discharge events at the inception level, in our work we went even below that. Another difference between Tanaka's data and our data is that he performed his work on solid dielectrics whereas we carried out our experiments in air gaps. Certainly a central difference between Tanaka's results and ours is the different time-scale he used. He recorded much faster individual events, whereas we registered rather integrated PD signals (due to the limitations of our circuitry).

As mentioned above, a change in PD waveform occurred as the air gap increased. This suggests a change in PD mechanism from a pulsive type to a more blurred type of PD, *ie* to a type of PD which lasts for longer and has a much less magnitude. This fact was evident in previous publications [5, 6]. This change — as the air gap gets larger — suggests a pulseless type of mechanism. Such transitions have been observed before even though the researchers have used insulating materials other than air [11].

The present work indicates that there may be PD phenomena below the inception voltage or in other words, in the strict context of the present work, above the so-called critical air gap. The implications of such findings were mentioned in previous work [2, 3], namely that, there may exist insulating material damage even below inception voltage. Proposed lifetime models may have to be modified, and new parameters, taking into account the existence of very small PD, may be taken into consideration [3, 11].

The present work stresses the fact that evidence exists, which points out that "something" may happen even below the inception voltage or, in our case, even above critical gap spacing. If this is so, then the classical formulae giving the lifetime of an insulation may be reconsidered. Indeed, as was remarked in [6], if what is claimed here is true, there is probably not a threshold electrical field below which no material damage is possible, *ie* no deterioration and/or degradation takes place. In other words, the well known formula $L = c(V - V_0)^{-k}$ (where L the time to failure, V the applied voltage, V_0 the voltage below which no deterioration takes place and k a constant) may have to be modified to $L = cV^{-k\cdot}$. To put it in other words, according to [2], "most equipment designers use this empirical relation without having settled the fundamental question as to whether $V_0 = 0$ or not, since empirical experiments in reasonable time periods cannot distinguish between the two forms".

The present paper by no means concludes the question of very small discharges below the inception voltage (or above a critical gap spacing). It is not to be excluded that the pulsive waveforms reported in Fig. 2, for example, are due to significant current densities related to volume charge densities at the point electrode [12]. This aspect has to be further researched also in connection to the field enhancement in the vicinity of the point electrode together with the extent of the ionization region [13].

One may object to the term we use in the context of this work, namely discharges below inception voltage or discharges above a critical gap spacing. There was some criticism, that since we still measure discharges, we cannot claim we are below inception voltage [14]. Others supported the view that it would be more appropriate to use the term "charging phenomena" [15], and yet others talked simply about "ionizing phenomena". A proposal to consider that after a certain voltage we measure so many discharges per unit time, can also be thought of seriously. One has the impression once again that there is a problem of definitions, as was the case in some other phenomena related to partial discharge mechanisms [16, 17]. In the present case, however, the fact is that discharge waveforms are recorded, even for gap spacings exceeding the critical gap spacing. The recorded waveforms are certainly ionizing phenomena, this term, however, is very general encompassing a multitude of events. To define, on the other hand, a certain number of discharges per unit time, can be a reasonable proposal but one can continue to argue about the number of discharges which might be preferred. The term "charging phenomena" is also a reasonable proposal but it somehow contradicts the fact that we register precise waveforms. The question of definitions, even in this region of somehow blurred phenomena, remains with us and is in great need of an answer.

A further criticism which may be leveled at the present work is, that it refers to partial discharges in the msec range and not in the microsecond or even in the nanosecond range. Due to the detecting circuit used (with its considerable time constant), it was natural to detect waveforms of the shape and times we detected. One may say that such PD signals are rather integrated signals and not just individual discharges. This may well be the case. This, however, does not mean that the general trend we recorded is not true. The mere fact remains that even beyond the critical gap, discharges can occasionally be registered. This agrees with the gist of papers such as [2, 4, 5, 6, 8, 18].

Another point should be raised regarding this work: one can object to the term inception voltage since the discharges registered above a critical gap were intermittent. According to the seminal study by Kelen [19], inception voltage refers to the lowest voltage at which discharges of a specified magnitude recur in successive cycles when an increasing alternating voltage is applied to the insulation, whereas ignition voltage is the voltage that must be applied between conducting or dielectric surfaces to cause a discharge in the gas between them. One may object to the use of the term "inception voltage" since in the context of this work we did not have alternating voltages. The gist, however, of the whole approach does not change: irrespectively of the definitions used, the fact is that discharges above a critical gap exist, no matter whether they are regular or intermittent. This aspect can be further stressed: the cumulative effects of discharges — even the very small ones — consist of heating and mechanical impact of shock waves [19]. Such a statement applies equally well — albeit to a different degree of intensity — to regular and to intermittent discharges, to low magnitude as well as to high magnitude discharges. Relevant studies can be seen in some classical publications [20–22], as well as in some more recent ones [23–27].

A further point of contention may be that with the present experimental arrangement, we register rather corona events and not partial discharges. The criticism lies on the fact that we used air as insulating medium and not a solid dielectric. Again, the answer to this criticism is that it is matter of definition: corona or PD, the truth is that we have ionizing phenomena below the critical gap spacing. And again, the gist of our main thesis is the same: ionizing events do occur and they are recorded. As a further validation of out main thesis the definition from a well known book is cited [28]: Sometimes, the terms "partial discharge" or "internal discharge" are used instead of corona discharge to describe the [same] phenomenon.

It should be pointed out that in the context of this work, no statistical study of the registered phenomena was performed. The principal aim of this work was to indicate that there are possible PD phenomena registered even above the so-called critical gap. To the criticism which was aired by some colleagues, namely that the insulation community is not that familiar with the term of the critical gap, one has to say that it may well be understood if one takes into account that in this work we did not have a variable applied voltage but a constant applied voltage of 7.5 kV. Furthermore, this work used the term "critical gap spacing" and not the classical term "inception voltage", which really means the critical voltage below which no degradation takes place [28]. Both terms, however, amount to the same, namely that there are PDs (or charging or ionizing phenomena) outside these well defined regions, *ie* below inception voltage and at gaps larger than the critical gap.

A final point should be stressed: although no distinctive correlation has been established between the size defects and breakdown voltage or lifetime of solid insulation regarding PD events above inception voltage [29], it is not futile to search the charging (or ionizing) events at lower voltages since there is indication (even scarce for the time being) that these may be deleterious to the insulation.

5 CONCLUSIONS

In this paper it was shown that there may be PD phenomena even above the critical air gap or, if we put it in more general terms, there may PD phenomena even below the so-called inception voltage. This may have serious implications for the insulating systems since there were occasions in the past when industrial insulating systems broke down suddenly after only a short while in service and after having gone through all the necessary international standards testing. The data presented here supports evidence offered by other researchers on similar phenomena below the so-called inception voltage with solid insulating materials. The gist of this paper is that, no matter the particular definitions about PD, corona, inception or ignition voltage, there are indications as to the existence of ionizing events at low voltages and/or at gap spacings larger than the critical one.

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