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DETECTION AND REGISTRATION OF PARTIAL DISCHARGE EVENTS BELOW THE SO–CALLED INCEPTION VOLTAGE: THE CASE OF SMALL AIR GAPS

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The question of insulation damage from partial discharges below the so-called inception voltage has not been the subject of intensive research as were other topics in high voltage engineering. Indications of possible insulation damage were given previously. In this paper, small air gaps are investigated with a fixed voltage of 7.5 kV and a non-uniform electrode arrangement. It is shown that random discharges below inception voltage exist. Experiments were carried out with a point-plane electrode arrangement, the point electrodes being of various diameters. The implications of such discharges are discussed.

K e y w o r d s: small air gaps, inception voltage, partial discharges, point-plane electrode arrangement

1 INTRODUCTION

The questions regarding insulation because of partial discharges (PD), PD detection and mechanisms of PD have been dealt in various publications [1–3]. 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 [4, 5]. In those papers, 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 the papers [4, 5] were significant, in that they explained to a certain extent sudden failures of insulating systems [6] — even though these systems had passed the prescribed tests — and also in that they could point out to the direction of improving polymer formulation and, moreover, to a different approach to ageing insulation models [7]. Recent work performed with small air gaps and point-plane electrode arrangements, confirmed that random discharges may occur below inception electric fields [8, 9].

It is the aim of this paper to further elaborate the above mentioned concepts and to see whether the conclusions offered in [8, 9] are valid also with different point electrode diameters.

2 EXPERIMENTAL ARRANGEMENT AND PROCEDURE

In this paper, a small Greinacher generator was used [9, 10]. 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 the discharges were continuous bridging the gap in most occasions. Bearing in mind that the Greinacher generator produced 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 goes without say that if discharges were taking place at larger air gaps, this would mean that random PD events would also happen below the inception.

3 EXPERIMENTAL DATA

The needle electrode can be seen in Fig. 1 (expanded view). The maximum electric field developed at the tip of the needle is given by the well known Mason's formula [11]

$$E_{\max} = 2sE_{\text{avg}}/r1n(1 + 4s/r) \qquad (1)$$

where, $E_{\max}$ is the field at the needle tip, E_{avg} is the average electric field applied to the gap ($= V/s$, where V is the applied voltage), s 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 programme, communicates the PD information to a personal

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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 s	14767	10.714	38.062
0.75	15	4112	10	37.280
0.75	30	8977	10	37.280
0.8	25	5996	9.375	36.575
0.8	30	7137	9.375	36.575
0.85	20	4888	8.824	35.935
0.85	20	5359	8.824	35.935
0.9	5 min	336	8.333	35.351
0.9	10	9723	8.333	35.351
0.9	15	0	8.333	35.351
0.9	20	17629	8.333	35.351
0.95	10	2	7.895	34.815
0.95	10	959	7.895	34.815
0.95	20	0	7.895	34.815
0.95	20	386	7.895	34.815
0.95	30	10	7.895	34.815
0.95	40	0	7.895	34.815
0.95	60	4	7.895	34.815
1	10	0	7.5	34.320
1	12	0	7.5	34.320
1	30	0	7.5	34.320
1	55	0	7.5	34.320
1	60	0	7.5	34.320
1.05	20	0	7.143	33.861
1.05	35	0	7.143	33.861
1.05	60	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	10 s	2349	10.714	30.253
0.7	40	8415	10.714	30.253
0.8	15	2633	9.375	28.964
1	10	1509	7.500	27.021
1.2	10	1133	6.250	25.606
1.3	10	297	5.769	25.028
1.4	10	297	5.357	24.514
1.45	15	163	5.172	24.278
1.45	2 min	571	5.172	24.278
1.45	20	6675	5.172	24.278
1.5	1	0	5	24.054
1.5	5	0	5	24.054
1.5	10	0	5	24.054
1.5	10	16	5	24.054
1.5	20	5	5	24.054
1.5	30	2	5	24.054
1.5	35	0	5	24.054
1.5	40	10	5	24.054
1.55	15	0	4.839	23.840
1.55	45	0	4.839	23.840
1.55	60	0	4.839	23.840
1.55	70	0	4.839	23.840

computer and the results appear on its screen. The smallest pulse duration, experimentally found, was 12 μs. The control of pulses was performed every 10 μs and, consequently, there was sufficient time for the elaboration of each PD pulse by the micro-controller [10]. In Fig. 2, the whole experimental set-up can be seen. The resistor of 10 MΩ had a role of restricting damage because of the PD.

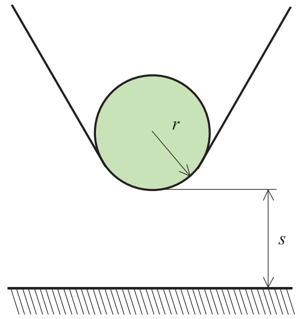

Fig. 1. Expanded view of the needle-plane electrode arrangement

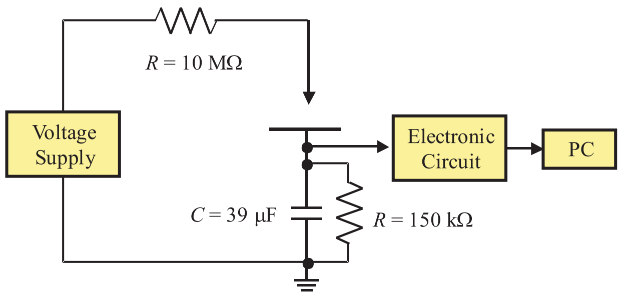

Fig. 2. Experimental arrangement used. By "electronic circuit" is meant the detecting and counting circuit incorporating a programmable micro-controller which transferred the number of recorded pulses to the PC (personal computer).

The resulting applied voltage was 7.5 kV and it was of negative polarity. The PD because of the negative polarity remind of the well known Trichel pulses mentioned in standard textbooks [12]. 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.

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 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 [9, 13, 14] 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

Table 3. Results for the needle diameter of 0.45 mm.

Air Gap (mm)	Exprerimental duration	Number of PD	E_{avg} (kV/mm)	E_{max} (kV/mm)
0.7	20 s	3289	10.714	25.655
0.7	15	2401	10.714	25.655
0.75	20	2795	10	25.038
0.75	25	3585	10	25.038
0.8	15	1994	9.375	24.485
0.8	25	3418	9.375	24.485
0.9	20	2314	8.333	23.530
0.9	35	2503	8.333	23.530
1	20	2143	7.5	22.732
1	35	3740	7.5	22.732
1.05	20	1548	7.143	22.379
1.05	35	2679	7.143	22.379
1.10	20	2321	6.818	22.052
1.10	35	3768	6.818	22.052
1.20	15	1564	6.25	21.463
1.30	35	1549	5.769	20.947
1.40	15	1373	5.357	20.489
1.50	15	975	5	20.079
1.50	5 min	1709	5	20.079
1.50	20	53	5	20.079
1.55	30	0	4.839	19.890
1.55	25	152	4.839	19.890
1.55	20	1012	4.839	19.890
1.60	60	0	4.688	19.709
1.60	15	3867	4.688	19.709
1.60	20	97	4.688	19.709
1.65	15	191	4.545	19.537
1.65	30	1628	4.545	19.537
1.70	20	0	4.412	19.373
1.70	30	0	4.412	19.373
1.70	40	0	4.412	19.373
1.70	60	0	4.412	19.373

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

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

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. As was noted in [13], this may suggest a change in PD mechanism, presumably from a Townsend-type mechanism to a glow-type mechanism. As the air gap becomes larger, and provided that the applied voltage remains the same, the PD gets weaker and its mechanism changes.

For the needle diameter of 0.25 mm and for air gaps smaller than 0.9 mm, continuous PD are observed (Table 1). For air gaps smaller than 0.9 mm a somehow darkened circular area on the plane electrode was observed just below the tip of the needle, at the distance which is the minimum between needle and plane electrodes. 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 (Tables 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 Bruning's terminology.

The results of the present study agree with the results of previous publications carried out in our laboratory [8, 9, 13, 14]. Taking into account the results of the present paper, Fig. 3 shows the variation of the critical air gap with needle diameter. Fig. 4 shows the already existing tendency, namely that the critical air gap increases with the needle diameter, including the results of the present work and of previous works [13, 14]. From Fig. 4, it is evident that there is a general tendency for the critical air gap to increase with the needle diameter.

Whereas Bruning and colleagues indicated that there are byproducts at and/or above inception voltage similar to those detected below it [4, 5], the present study validates his claims by presenting some indications of PD events even above the critical air gap. Sporadic PD events, below the so-called inception voltage, were also

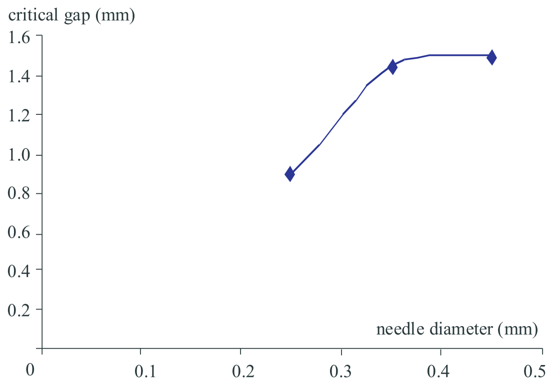

Fig. 3. Variation of critical air gap with needle diameter.

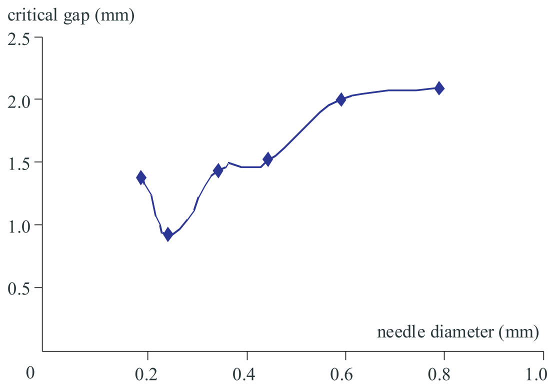

Fig. 4. Variation of critical air gap with needle diameter (including data from [13, 14]).

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

observed with polyethylene samples in other publications [15–17].

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 [18]. 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's data, although it refers to small air gaps and not to solid insulation, can be found also in Tanaka's work [19]. 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 [19] 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.

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 [9, 20]. This change — as the air gap gets larger — suggests a pulseless type of mechanism. This is possibly an indication of a glow discharge mechanism. Such transitions have been observed before even though the researchers have used insulating materials other than air [21, 22]. One might ask whether such work on small air gaps has any relevance to solid insulation problems and/or whether conclusions from the present work can be rightly inferred also for other types of insulation. The answer is that the results presented here are relevant to other types of insulation in as far as they indicate that notions like inception level, inception stress, inception voltage etc. are dependent on the quality of the detecting equipment and that there is not a clear-cut separation between inception and non-inception level. This becomes all the more important in that there is a remarkable intermittency of PD phenomena below inception. More work has to be devoted to PD phenomena at and below inception level. It is not only that such phenomena may have deleterious effects on the insulation. It is also that, with more research below the inception level, one will be able to see, in the case of solid insulation, what sort of minute cavity sizes — under the appropriate conditions — may initiate PD. This may have as a consequence the improvement of the detectability of conventional PD detecting equipment.

Another question might be arisen as to whether such recorded PD phenomena are indeed PD or whether they are just charging phenomena [23]. This view, expressed by Muhr, proposes the term "charging phenomena" since, according to his opinion, it is inappropriate to talk about PD below inception level. The recorded waveforms of such phenomena, however, as reported in previous publications [9, 20], suggest they are PD. However, even if they were just PD charging phenomena, that would not change much our approach regarding the danger which emerges to the insulation.

The present work indicates that there may be PD phenomena below the so-called 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 papers [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 [24].

It is proposed, as a further effort to elucidate the aspect of small PD below the so- called inception level, to attack the whole problem in two ways: first, to try to record in a more refined way the number of small PD, their phase angle and their magnitude, *ie* to try to use a Pulse Height Analysis (PHA) to record the manifested phenomena and second, to try to record the waveforms of such small PD in order to be informed more about the true nature of such PD. Such approaches were discussed already in previous papers [25–27], albeit not with very small PD.

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.

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