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COMMUNICATIONS

ON THE DAMAGE OF INSULATING MATERIALS BELOW INCEPTION VOLTAGE

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Although much work has already been done on the issue of partial discharges and their damaging consequences at and above inception level, the possibility of insulating material deterioration below the aforementioned level has not been investigated thoroughly yet. This paper indicates that there is evidence of partial discharge activity even below the inception voltage. This activity seems to be of intermittent pulsive nature. The present paper also points out possible directions for future research in this field.

K e y w o r d s: partial discharge, inception voltage, insulation lifetime

1 INTRODUCTION

Partial discharges (PD) constitute a major threat for the lifetime of an insulating material and/or system [1-3]. They result from charge injection and space charge formation and they may lead to electrical treeing and ultimate failure of the insulation [4, 5]. PD appear at the so-called inception level, *ie* the lowest voltage at which discharges of a specified magnitude recur in successive cycles when an increasing alternating voltage is applied to insulation [6]. Although much work was devoted to the study of the behaviour of PD at or above the discharge-inception voltage, not enough attention was paid to what might happen to the insulation below this level. This paper has the intention of presenting work that has been performed in the regime of voltages just below the so-called inception level and of suggesting further possible research directions.

2 SOME DEFINITIONS RELATED TO PARTIAL DISCHARGES

In the context of the present paper, it would be useful to clearly define certain quantities related to PD events. Let us make clear that we try to tackle here the topic of internal discharges. As internal discharges are defined PD in cavities or at the edges of conducting inclusions in solid or liquid insulation [6]. The terms "partial discharge" and "corona" are used by some authors interchangeably, since, in their own words, these authors "... have not been able to find a meaningful quantitative, circuit related, plasma characteristic definition differentiating between these two terms" [7]. Let us also say that the cavity may be entirely enclosed in insulation, or it may be covered on one side by a conductor [6]. As discharge magnitude is defined the loss of charge, as measured at the terminals of a sample, caused by a single discharge [6]. As discharge energy is defined the energy dissipated by a single discharge. Furthermore, the discharge-inception voltage has to be distinguished from the discharge-ignition voltage which is the voltage that must be applied between conducting or dielectric surfaces to cause a discharge in the gas between them. It is to be emphasized that the inception voltage depends on the sensitivity of the detecting discharge equipment. As sensitivity of a PD detector is defined the smallest discharge magnitude that can be registered by the said detector.

3 HISTORICAL BACKGROUND

The incentive for this work was given by the unexpected failure of large rotating machines with cast polymer insulation in the fifties in the USA. Those machines failed in field use after only a few months despite the fact that they passed all the diagnostic tests available at that time. Further failures of 15 kV cast epoxy insulated switches - which indicated discharge inception voltage well above operating voltage when first manufactured - gave some more food for thought during the sixties. Similar failures have been observed in underground polyethylene cables in more recent years [7]. The difficulty of explaining such failures in industry prompted some to think in terms of possible damage of insulation below the discharge inception voltage. The basis for further work was given by [8], where the idea was propagated that electrical energy dissipation below discharge inception voltage might be responsible for progressive slow failures that have been observed. Moreover, it was shown that, in an enclosed cavity, a low voltage could induce very small currents (well below the inception level) that would lead to a temperature increase inside the cavity and also on its sur-

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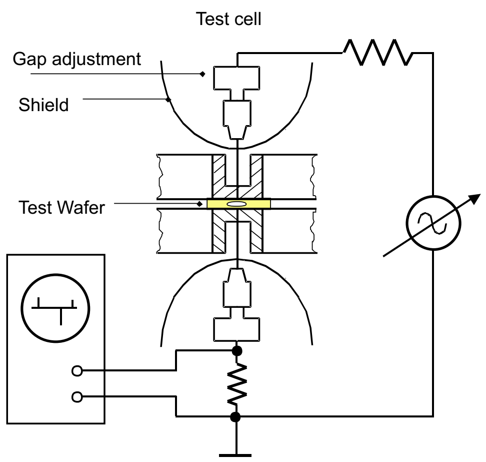

Fig. 1. Axial symmetric test cell. Replaceable test wafer with cylindrical rest cavity (after[13]).

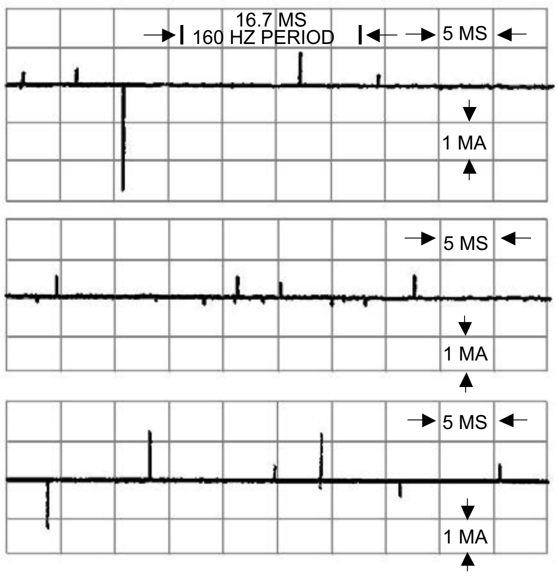

Fig. 2. Typical variations in current traces at start, and at 5 and 105 minutes in 200 minute ageing run at 2.5 kV, - as captured by Tektronix 2230 oscilloscope (after[13]).

face walls. The latter would lead to a slow deterioration of polymers.

A further thought provoking paper was published some years ago [9], where it was stated that ageing of polymer insulation by voltages below the discharge inception voltage does indeed exist and that this can be used to determine the necessary reduction in voltage stress in order to ensure long insulation life.

It can clearly be seen from the small number of relevant references that the problem of possible discharge damage below the discharge inception level has not drawn enough attention over the years, although it is a problem to be reckoned with. Part of the difficulty of the problem consists of the uncertainty of a clear definition of the discharge inception voltage. Let us also bear in mind that the discharge inception voltage is a statistical quantity [10]. As said, the inception voltage is defined by the sensitivity of the available detecting equipment. It has also not to be forgotten that the main thrust of research in the past decades was given to the discharge events at or above the inception voltage [11].

4 EXPERIMENTAL ARRANGEMENT, RESULTS AND DISCUSSION

As explained in [7, 12] the effort concentrated to demonstrate the possible existence of PD events and material deterioration with an experimental arrangement which would simulate a cavity inside a solid dielectric subjected to a uniform electric field. The main electrode arrangement which was used was that of Fig. 1. The construction of the electrode arrangement was based on the idea that inhomogeneities in polymers provide a current path to a cavity which will supply the equivalent of a point electric field condition at the surface of the polymer local inhomogeneity. The top electrode could be adjusted with respect to the bottom electrode by means of a micrometer. Both electrodes were easily replaceable. The polymer samples could also be easily replaced. Depending on their shape (planar or point electrodes down to 1 μm diameter) they were positioned either in the polymer cavity or to controllable distances from the end surfaces of the polymer insulation over the cavity axial ends [12, 13]. Furthermore, the electrode arrangement was capable of operation for many hours at low average current. Shield electrodes and precision spacers were also incorporated in the said arrangement.

The cavity in all tests had a diameter of 0.97 mm and 2.54 mm height. An antioxidant free high molecular weight polyethylene was used as an insulating sample. Point electrodes of 58 μm diameter were used. The current traces were recorded with the aid of a Tektronix 2230 oscilloscope and a 50 Ω resistor. A 60 Hz *ac* voltage through a 60 MΩ resistor on the *hv* side was applied. Figure 2 shows typical variations of registered partial discharge currents during a 200 min test (of the same duration were also the tests performed at lower voltages). Tests were carried out at 2.5 kV. It should be noted that PD with a conventional discharge detector were recorded above 3 kV (the sensitivity of the PD detector was 0.1 pC). Such measurements were repeatable. The nature of these current traces was random and their magnitude was in the range of 1 - 10 mA. Further PD current traces, at 2.25 kV, can be seen in Figs. 3 and 4 (different scales used). The magnitude of the PD currents in the latter cases was in the range of some tens of mA. For even lower applied voltage, at 2 kV, PD current traces were again recorded (Fig. 5). The PD current magnitude in this case was about 0.2 mA. It is obvious from Figs. 2 - 5 that for voltages well below inception, PD currents were registered that were in the range of about 0.1 - 80 mA.

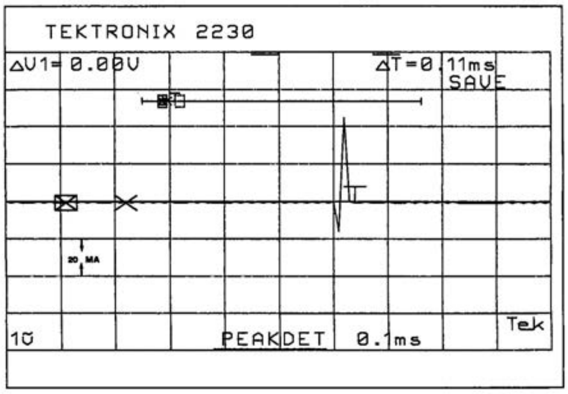

Fig. 3. Current traces at 2.25 kV. Symbols displayed are analysis markers of Tektronix 2230 osciloscope

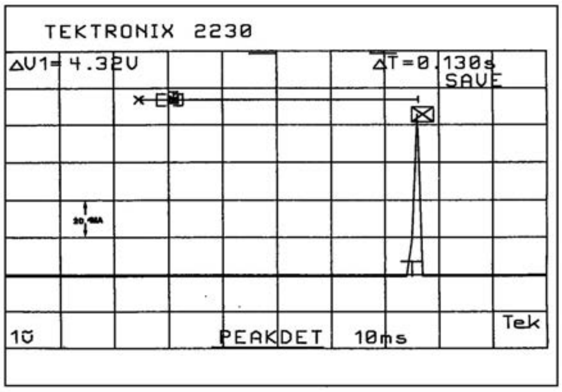

Fig. 4. Current traces at 2.25 kV in Figs. 3 and 4 were taken at different instances during a 200 minute ageing run

The above indicates that even minute PD currents may be present in cavities having inhomogeneities on their surfaces. The recorded PD currents were pulses.

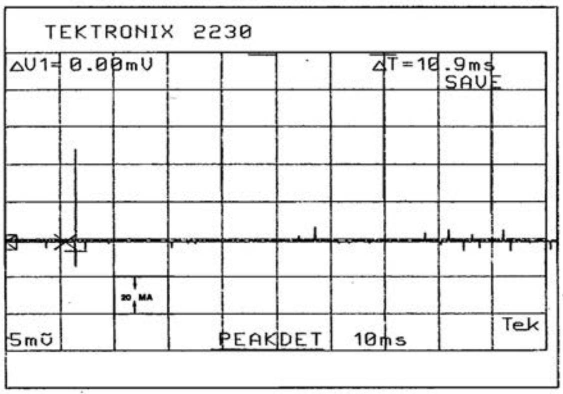

Fig. 5. Current traces at 2 kV (results taken during a 200 minute ageing run

In similar tests, X-ray Photoelectron Spectroscopy (XPS, otherwise named electron spectroscopy for chemical analysis (ESCA)) was employed in order to see the chemical constituents of the inner cavity walls during the tests below the inception voltage. This technique has the capability of detecting elements in the first few atomic layers of a solid surface. It has been found that chemical changes, similar to those appearing when the insulation sample was exposed to a voltage causing partial discharges, were detected [12]. More precisely, similar nitrogen species were observed when the insulation sample was stressed by voltages both at and below the inception level. Organic functional groups from the tests at and below inception level can be seen in Table 1. As Bruning and colleagues [12] put it, "Since corona currents and resulting species lead to failure of polymer insulations in relatively short times, this bears strong evidence that subcorona aging can lead to serious damage, even though a partial discharge detector shows the insulation is being operated below the CIV level". The consequences of such findings are significant since they show that there are strong indications that there is insulation damage below the inception voltage.

Table 1. Possible reaction moieties from both corona and subcorona ageing runs (after[12])

O=C–OH		
C=O	–NH	$-NO_3$
C–OH	$-NH_2$	$-NO_2$
C–O–C	C=C	–N–O

The pulsive nature of the partial discharge currents has also been indicated in a number of other papers [14-17], where a different electrode arrangement was used and the PD behaviour was studied in the proximity of inception voltage. In that case polyethylene films containing a cavity in the middle of them, have been sandwiched between two plane electrodes. PD currents were recorded with rise times in the range of 1 ns, their magnitude being higher than that in the range of mA [18]. If one considers the results of [12], the results presented in the present paper, and those of [14-17], it is evident that, below inception, there is a regime of intermittent stochastic PD, whereas at or slightly above inception PD appear regularly. This can somehow be explained by the gas conduction process inside the cavity as was mentioned in [12]. In the latter reference, the cases of discontinuous nature or of a smoother gaseous PD onset were discussed and it was shown that the more pronounced the non-uniformity of the electrode arrangement the greater the range of voltage over which there is a PD current below inception.

The research work presented here indicates that discharge activity below the so-called inception level can be manifested as pulses. This of course does not exclude the existence of other forms of discharges. A cavity enclosed in a solid insulation can be considered as a source of current pulses. It can also be considered as a source of a certain electromagnetic spectrum. These aspects have been theoretically analyzed in [19] and experimentally studied and discussed in [20, 21]. In [19] it is also pointed out that from such a cavity a continuous current flow is not expected, something which can be seen from the results presented in this paper.

5 PROPOSALS FOR FUTURE RESEARCH

In order to even more validate the points raised here, further work is planned in this field. The next step will be to investigate the events below the so-called inception voltage with the aid of a point-plane electrode arrangement. Insulating material will be either air or polyethylene films with air as surrounding medium. The arrangement will be supplied by a small Greinacher generator. This produces invariably 7.5 kV and PD are recorded with a small gap spacing. The idea is to increase the gap spacing and see whether, even below the inception level, we register random discharges. The whole sequence of discharge pulses will be stored for further work in a personal computer. In this way, one hopes to get more evidence on the possible PD events below the inception level.

Further work is also planned with the electrode arrangement of Fig. 1 on a variety of polymers since our effort is to establish whether such phenomena take place in as many insulating materials as possible. Repeated tests with the experimental apparatus described in [12] gave results confirming compositional changes on polyethylene cavities [22]. Such a series of tests is also in line with the conventional wisdom expressed in the technical literature, namely, that the resulting by-products may have deleterious interactions with the healthy part of the insulation [23]. Further work on some aspects of the chemical side of the problem should also be done. The tests mentioned previously have been carried out at ambient temperature. The question of PD below inception becomes even more important when dealing with elevated temperatures since thermal ageing of a polymer above the glass transition temperature T_g (the temperature at which there is sufficient thermal energy for long range chain segment motion) generally increases crystallinity unless the temperature is so high that the polymer degrades. Although in the present work an antioxidant free polymer was used, the role of additives (such as plasticizers, UV stabilizers, slip agents) which may influence the crystallization of the polymer, should be investigated in the light of the existence of PD below inception [24].

A criticism expressed recently regarding the possible insulation damage below the so-called inception voltage, was that, since the extinction voltage is lower than the inception voltage, discharge events at or below inception become essentially blurred [25]. In view of this criticism, and since the topic of possible insulation deterioration below inception is of industrial interest [26, 27], long time testing and observation of discharge events at inception voltage are planned. The purpose of this test will be the variation of inception voltage with time. A possible decrease of the inception voltage may mean that "latent" discharges are at work. Such inception voltage decreases, although in a different context, have been observed with epoxy samples [28, 29].

6 CONCLUSIONS

The present work shows that there are indications that chemical changes in the insulation at or above inception are similar to chemical changes below inception. Moreover, discharge events below inception manifest themselves as pulses. Such currents are of the order of some tens of mA and of random nature.

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