Journal of ELECTRICAL ENGINEERING, VOL. 56, NO. 9-10, 2005, 246–251

EXPERIMENTAL RESULTS WITH SMALL AIR GAPS: FURTHER THOUGHTS AND COMMENTS ON THE DISCHARGE (OR CHARGING PHENOMENA) BELOW THE SO–CALLED INCEPTION VOLTAGE

Michael G. Danikas — Nikolaos Vrakotsolis *

There has been some research effort on the problem of possible partial discharges (or charging phenomena) below the so-called inception voltage in both solid and gaseous dielectrics. In the present paper, we offer more experimental results on the existence of random partial discharges for a range of small air gaps at electric fields corresponding to the inception voltage or below it. There are strong indications that random partial discharges (or charging phenomena) appear in air gaps greater than those at which discharges normally take place. The connection of the present results with those of previous work is discussed. Some thoughts on possible future work are proposed.

Keywords: small air gaps, inception voltage, partial discharges, point-plane electrode arrangement, space charge

1 INTRODUCTION

Research on very small partial discharges has already been reported [1]. The problems arising from possible small partial discharge activity — not always detected by the discharge detectors — have also been discussed in various publications [2, 3]. In these papers, it is indicated that very small partial discharges may cause damage to the insulation even below the so-called inception level. The consequences of such discharges for the insulation lifetime are obvious.

Previous published work tackled the question of small random discharges in small air gaps and it was indicated that such discharges appear in air gaps larger than the air gaps at which normally breakdown takes place [4]. Such small discharges may influence the breakdown voltage and the lifetime of the air insulation. The present paper is an extension of previously published work.

2 ELECTRODE ARRANGEMENT AND EXPERIMENTAL PROCEDURE

In this work, as was also the case for [4], a small Greinacher generator was used [5]. The generator produces invariably 7.5 kV. This voltage applies to a needle-plane electrode arrangement with the needle electrode having a radius of 0.3 mm. The discharges were detected with a typical R–C circuit ($R = 150\,\mathrm{k}\Omega$, $C = 39\,\mu\mathrm{F}$). This detecting circuit registered discharges for a variety of gap spacings. The discharge waveforms — as were registered by an oscilloscope (described briefly below) — were in the range of μs. As is understandable from the above, the time constant of the detecting circuit was much higher than the discharge decay-time constant [5]. A Greinacher generator (which is, in the context of our work, a fixed voltage source) was used because it was thought more convenient to study such phenomena with a single polarity rather than with an AC voltage. The polarity of the DC voltage was negative.

Normally, when the experimental set-up discharges, Trichel pulses are produced. These pulses are shown on the screen of a Tektronix oscilloscope (type 7623 A, bandwidth 20 MHz). As was noted in [4], there is freedom of movement of the lower plane electrode with respect to the upper needle electrode. The distance between the electrodes was measured with feeler gauges.

The electrode arrangement normally discharges when the air gap is 1.80 mm (in other words, the inception voltage for this gap is 7.5 kV). With the gap set at 1.80 mm (and certainly with smaller air gaps) the recorded discharges are continuous. Having in mind that the voltage is fixed at 7.5 kV, it would be interesting to see whether discharge phenomena persist — even intermittently — at air gaps larger than 1.80 mm. If this is the case, that would be an additional indication of the fact that discharge phenomena may appear for electric fields below the inception field. Moreover, evidence of such discharge events will be given in the form of oscillograms.

3 REGISTRATION SYSTEM OF DISCHARGES AND CALCULATION OF ELECTRIC FIELDS

An expanded view of the needle-plane electrode system is shown in Fig. 1. The recording of partial discharges was carried out with a detecting and counting electronic circuit which incorporated a programmable

---

* Democritus University of Thrace, Department of Electrical and Computer Engineering, Electric Energy Systems Laboratory, 67100 Xanthi, Greece

ISSN 1335-3632

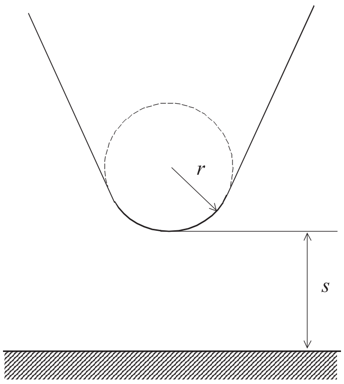

Fig. 1. Expanded view of the needle-plane electrode arrangement.

Table 1. Results of tests performed with a gap spacings of 2 mm, 2.05 mm and 2.10 mm. Also shown the testing time, the number of discharges, and the maximum field $E_{\max}$.

Gap spacing (mm)	Testing time (min)	Number of discharges	Maximum electric field $E_{\max}$ (kV)
2	30	19	15.05
2	30	10	15.05
2	30	513	15.05
2	30	1125	15.05
2	45	7161	15.05
2	45	3721	15.05
2	60	3537	15.05
2	120	14310	15.05
2.05	120	12	14.95
2.05	120	231	14.95
2.05	120	105	14.95
2.05	120	45	14.95
2.05	60	0	14.95
2.10	120	0	14.84
2.10	120	4	14.84
2.10	120	10	14.84
2.10	75	0	14.84
2.10	120	0	14.84

micro-controller. The latter is programmed in order to register and to add discharge pulses which are applied at its input, *ie* discharges which occur in the air gap. It was experimentally found that the smallest pulse duration, which can be measured, is $12\,\mu$s. The control of pulses was performed every $10\,\mu$s, consequently, there was sufficient time for the elaboration of each pulse by the micro-controller [6]. In Fig. 2, the whole experimental arrangement is shown.

The maximum electric field $E_{\max}$ which is developed at the tip of the needle electrode is given by

$$E_{\max} = 2sE_{avg}/[r\ln(1+(4s/r))] \qquad (1)$$

where, $E_{\max}$ is the field at the needle tip, E_{avg} is the average electric field applied in the air gap ($E_{avg} = V/s$), s is the electrode gap spacing and r is the radius of the needle tip [7]. Having in mind that $s = 1.80$ mm, the applied voltage $V = 7.5$ kV (hence, $E_{avg} = 7.5/1.80 = 4.16$ kV/mm), $r = 0.3$ mm, we have that $E_{max} = 15.59$ kV/mm.

4 EXPERIMENTAL RESULTS AND DISCUSSION

In a previous publication, we set the distance between the electrodes at 2 mm (a distance distinctly larger than 1.80 mm) and the discharge phenomena became intermittent [4]. In the present work, a distance of 2 mm gave again intermittent discharges. Furthermore, gap spacings greater than 2 mm gave also random discharges. That happened up to the air gap of 2.10 mm. The following Table 1 gives in detail the results regarding the testing time, the number of discharges for the gap spacings of 2 mm, 2.05 mm and 2.10 mm and also the corresponding $E_{\max}$ (it should be noted that the values shown in this Table are not the values of all performed experiments. They are just values of some experiments). Evidently, there is still discharge activity even above the gap of 1.80 mm (which, we repeat, is the gap giving normally discharges). For gaps greater than 2 mm, random discharges are observed. The number of discharges — as the gap increases — decreases substantially. Such intermittency represents another validation of the conclusion offered by Bruning and colleagues, namely, that even below the so-called inception voltage (or inception field) discharges can indeed appear [2, 3, 8, 9].

An objection which can be raised — talking about discharge phenomena below inception — is the following: how can somebody talk so freely about 'discharge phenomena' below inception? If there are indeed 'discharge phenomena' below inception, then can we rightly say that there is a lower inception voltage than the one we thought to be valid? Such objections raised by Muhr [10], who proposed the term 'charging phenomena' instead of 'discharge phenomena'. In fact, no matter if we define them as 'discharge' or 'charging' phenomena, the truth is that these phenomena occur below the so-called inception level. However, evidence from some oscilloscope measurements of the registered pulses may convince the reader that the aforementioned phenomena are discharges and not just charging events.

Discharge pulses were registered with a digital Tektronix oscilloscope type TDS 224 and of bandwidth 100 MHz. The observed pulses are shown in real time on the screen of a computer with the aid of suitable software (Wavestar). The latter gives the possibility to process and to store the various pulse shapes. In Fig. 3, discharge pulses with an air gap of 1.80 mm are shown. In Fig. 4, discharge pulses with an air gap of 1.90 mm are shown. In Fig. 5, discharge pulses with an air gap of 2 mm are registered. The shape of the pulses does not appreciably change even for an air gap of 2.05 mm (Fig. 6). It is observed that the pulse shape changes when the air gap becomes 2.10 mm (Fig. 7). In Figs. 3–6, the shape of the pulses was pointed, which seems to suggest that

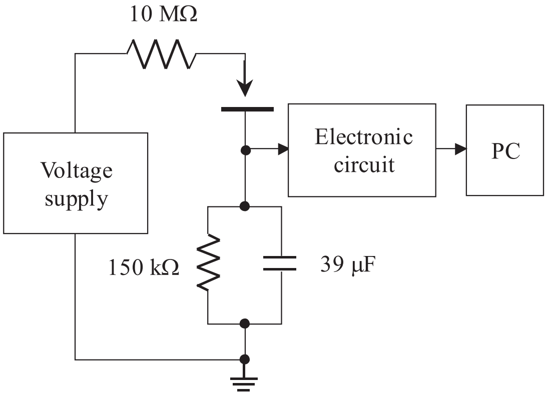

Fig. 2. Experimental arrangement used. By 'electronic circuit' is meant the detecting and counting circuit incorporating a programmable micro-controller which transferred the number of recorded pulses to the PC (personal computer).

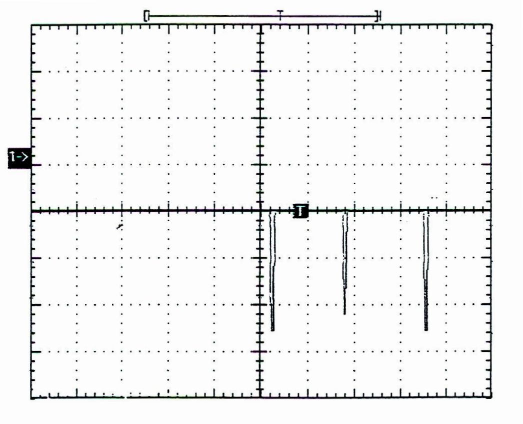

Fig. 3. Discharges with an air gap of 1.80 mm which were registered after a test period of 10 min (200 V/Div, 1 ms/Div). The shape of the recorded waveforms suggests a Townsend type of mechanism.

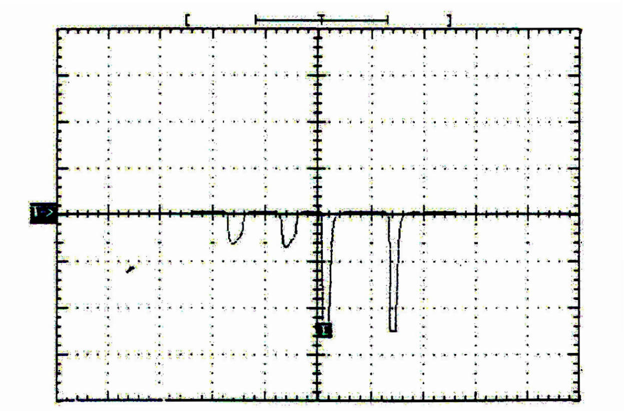

Fig. 4. Discharges with an air gap of 1.90 mm which were registered after a test period of 26 min (100 V/Div, 1 ms/Div). The shape of the recorded waveforms suggests a Townsend type of mechanism.

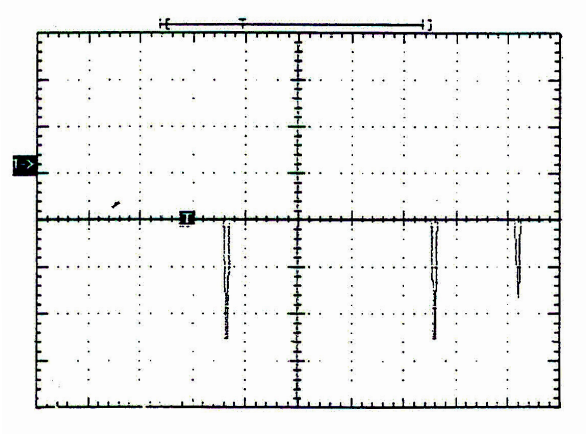

Fig. 5. Discharges with an air gap of 2.05 mm whch were registered after a test period of 55 min (50 V/Div, 1 ms/Div). The shape of the recorded waveforms suggests a Townsend type of mechanism.

a discharge mechanism being probably of the Townsend type is at work, whereas in Fig. 7 the shape of the pulse shows a pulseless mechanism. What does this mean? It probably means that there is a change of discharge mechanism as the air gap gets larger. The discharge from the pulse-type transforms into a pulseless discharge which indicates the existence of a glow discharge mechanism. Such transitions — from pulse to pulseless discharges — have been already observed in other insulating materials [11–14]. Furthermore, it is evident from [15], that pulseless discharges in cavities in epoxy resin have a shape similar to that of Fig. 7. Again, according to [15], the appearance of such discharges does not minimize the danger for the insulation. This might suggest a common denominator regarding partial discharge transition mechanisms, no matter if these take place in air or in a solid dielectric. This suggestion, however, has to be further validated.

In [4], we wrote that discharges with an air gap of 2 mm become intermittent. This holds true also for the present publication. At 2 mm, discharges were recorded that were erratic. Indeed, sometimes discharges in their thousands were registered (see Table 1), whereas in other experiments very few discharges were recorded (*eg* , for a test duration of 30 min, on one occasion only 19 discharges were recorded, in another test of equal duration only 10 discharges and yet in another test 1125 discharges). By looking the results of Table 1, one might say that these are not always repeatable. The non repeatability of some of the results of the discharges may be due to the fact that such phenomena are inherently statistical. Regarding the long-lasting discharge activity, as is the case in this work and bearing in mind that the polarity of the needle is negative, this depends on the developed space charges. To be more precise, in the vicinity of the needle electrode, the electric field is greatly enhanced, the ionization region, however, is reduced. The consequence is that ionization might be terminated. The role of the needle surface should also be taken into account. The output work from the needle may also be slightly modified since the duration of discharge activity takes several tens of minutes and this in turn may influence the sporadicity of the discharges. The above seem to be in agreement with those mentioned in [5, 7]. Consequently, there is a qualitative agreement between the results of

[4] and the present paper, where a similar behaviour was noted. The discharges — as the air gap increases to values of 2.05 mm and 2.10 mm — are rendered even less numerous and more intermittent. No one may say for the time being with certainty whether such discharges — few in number and occurring randomly — are dangerous for an insulation. The fact is that *they exist* and as such they deserve the attention from the part of the researchers and other people concerned.

A further interesting point raised is that of Table 2. This Table shows the duration of the registered discharges and the change of the pulse height as the air gap changes. It is obvious that as the air gap increases, the duration of the discharges shows a somewhat increasing tendency (not that evident from Table 2 in which the detailed measurements are not shown). An opposite tendency is observed regarding the pulse height. The pulse height decreases with increasing air gap. At an air gap of 2.10 mm, the duration becomes far too great, in the range of ms. It is precisely at this point in time that we get the transition from pulse to pulseless discharges.

Table 2. Table showing the air gap, the pulse magnitude and the duration range of the pulses.

Gap spacing (mm)	Pulse height (V)	Range of discharge duration (μs)
1.80	290–520	100–300
2	12–125	60–100
2.05	8–120	100–400
2.10	65	6 ms

5 PROPOSALS FOR FUTURE WORK

Sporadic discharges may occur as the gap spacing increases beyond a ‘critical Value’. Such discharges may affect the insulation. The results of this paper — as well as those of [4] — agree with previous published work on solid insulating materials [2, 3]. Discharges not easily detected by conventional methods, especially if such events appear at/or below inception level, may indeed cause deterioration to an insulating system as was already reported [16]. We thus have strong indications on discharge events and their possible deteriorating role but not conclusive enough evidence. To do that, more similar research is needed on a variety of insulating materials (gaseous, solids and liquids) and also with a variety of electrode arrangements. Such research has not yet been undertaken, probably because it requires significant funding from the part of universities, research institutes and industry. It is, however, a task which has to be carried out. Recent work coming from companies and high technology research groups gives hope that the time for such a task has finally come [17].

A further point, strictly concerning the present work, which concentrates on discharges (or charging phenomena) in small air gaps *below the so-called inception voltage*, would be to take into consideration the way the electrodes are affected by the discharge activity. It is thought that such activity would change somehow the surface of the electrodes involved, and thus the difficulty with which charges would abandon these surfaces. In other words, the effects of electro-erosion should be taken into account and should be studied. Although the subject of the erosion of electrodes at or above inception voltage has already been investigated [18], little is known regarding the behaviour of the metallic surfaces at voltages *just below the so-called inception*. Furthermore, an arrangement with a faster oscilloscope should be used. An oscilloscope, possibly in the range of GHz, would register much faster discharge events and, consequently, would give more precise and detailed information on the gap spacings “critical values”. Such an approach has already been tried with success for enclosed cavities in solid dielectrics, albeit not with air gaps [19]. Needless to say that, in this case, a power source of greater versatility, than the one used in recent papers [4, 20], should be used in the future. A variable output voltage may give more substance to our claims, for a greater range of gap spacings. If this is realized, a comparison with already published results on similar experiments may be carried out [21].

The present work stresses the fact that evidence exists, which points out that even below the so-called inception voltage, discharges (or charging phenomena) are possible. If this is so, then the classical formulae giving the lifetime of an insulation have to be modified [2, 22]. Indeed, if what is claimed in the present publication is true, there is probably not a threshold electrical field (or voltage) below which no material damage is expected, i.e. no deterioration takes place. In other words, the well known equation $L = c(V - V_0)^{-k}$ (with L time to failure, V the applied voltage, V_0 the voltage below which no deterioration takes place and k a constant) may be reduced to $L = cV^{-k}$. As was noted in [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”. Future work should look at discharges (or charging phenomena) below inception voltage also in connection to electric field (or voltage) threshold and the above mentioned equation.

Finally, it must pointed out again that the work carried out in this paper concerns discharges in air, with small non-uniform field gaps without considering space charges. It is suspected by some, that the discharge pulses noted in Figs. 3–6, may be due to significant current densities related to volume charge densities at the point electrode [23]. This aspect should be seen in some detail in the future, in connection to the field enhancement in the vicinity of the point electrode together with the extent of the ionization region [24].

Last but not least, further elaboration should be done with respect to the data of the registered discharges regarding their magnitude and their number. Since it is

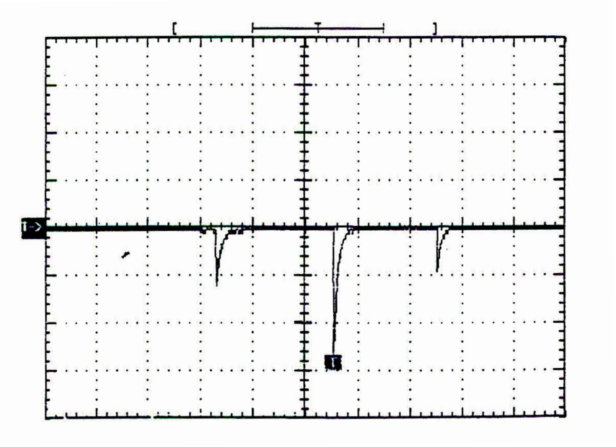

Fig. 6. Discharges with an air gap of 2.05 mm which were registered after a test period of 40 min (20 V/Div, 500 μs/Div). The shape of the recorded waveforms suggests a Townsend type of mechanism.

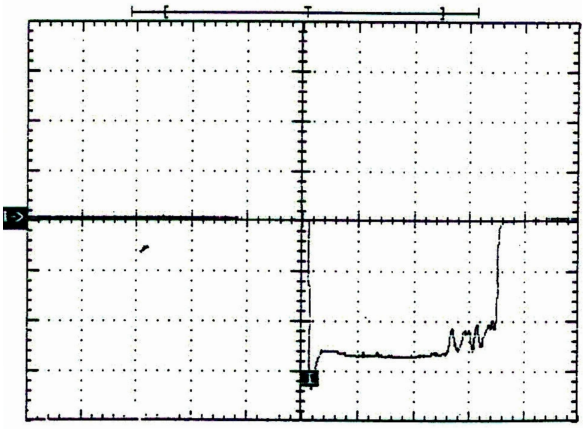

Fig. 7. Discharge with an air gap of 2.10 mm which was recorded after a test period of 54 min (20 V/Div, 2 ms/Div). The shape of discharge suggests a pulseless type of mechanism.

known that both the pulse magnitude and the pulse interval distributions may contribute to the error arising from the resolution times in cumulative counting, correction factors should be calculated so that a better use of the existing counting system can be made [25].

6 CONCLUSIONS

Using a non-uniform electrode arrangement, this publication gives some experimental data on random discharges that may appear even in air gaps greater than the maximum gap which is related to continuous discharge phenomena. It is shown that the discharges change from the pulse-type to a pulseless-type as the air gap becomes larger. The present experimental data offers evidence, namely, that discharges (or charging phenomena) are possible even below the so-called inception voltage. This publication also supports evidence presented by other researchers on similar phenomena below inception with solid dielectrics.

References

[1] DANIKAS, M. G.: Small Partial Discharges and Their Role in Insulation Deterioration, IEEE Trans. Diel. Electr. Insul. **4** (1997), 863–867/.

[2] BRUNING, A. M.—KASTURE, D. G.—CAMPBELL, F. J.—TURNER, N. H.: Effect of Cavity Sub-corona Current on Polymer Insulation Life, IEEE Trans. Electr. Insul. **26** (1991), 826–836.

[3] TURNER, N. H.—CAMPBELL, F. J.—BRUNING, A. M.—KASTURE, D. G.: Surface Chemical Changes of Polymer Cavities with Currents above and below Corona Inception Voltage, Ann. Rep. Conf. Electr. Insul. Diel. Phen., October 18–21, 1992, Victoria, B.C., Canada, 687–693.

[4] DANIKAS, M. G.: On the Discharge Phenomena Below Inception Voltage: Further Experimental Results with Air Gaps, J. Electr. Eng. **53** (2002), 58–60.

[5] AGUET, M.—IANOVICI, M.: Haute Tension, Lausanne, Suisse, Ecole Polytechnique Federale de Lausanne, Eds. Georgi, 1982.

[6] LIOUPIS, I.: The Problem of Detection (or not) of Very Small Discharges and their Consequences for the Lifetime of Solid Insulations, Diploma Thesis, Democritus University of Thrace, Xanthi, Greece, September 2000 (in Greek).

[7] MASON, J. H.: Breakdown of Solid Dielectrics in Divergent Fields, Proc. IEE **102 (Pt. C)** (1955), 254–263.

[8] DANIKAS, M. G.—BRUNING, A. M.: Comparison of Several Theoretical Sub-corona to Corona Transition Relations with Recent Experimental Results, Conf. Rec. 1992 IEEE Int. Symp. Electr. Insul., June 7–10, 1992, Baltimore, USA, 383–388.

[9] BRUNING, A. M.—DANIKAS, M. G.: Experiments on Polymer Cavity Currents Above and Below CIV, Ann. Rep. Conf. Electr. Insul. Diel. Phen., October 18-21, 1992, Victoria, B.C., Canada, 735–740.

[10] MUHR, M.: Private Communication, 3 June 2002.

[11] BARTNIKAS, R.—NOVAK, J. P.: On the Spark to Pseudoglow and Glow Discharge Transition Mechanism and Discharge Detectability, IEEE Trans. Electr. Insul. **27** (1992), 3–14.

[12] DANIKAS, M. G.—BARTNIKAS, R.—NOVAK, J. P.: Discussion on: On the Spark to Pseudoglow and Glow Discharge Transition Mechanism and Discharge Detectability, IEEE Trans. Electr. Insul. **28** (1993), 429–431.

[13] MORSHUIS, P. H. F.: Assessment of Dielectric Degradation by Ultrawide PD Detection, IEEE Trans. Diel. Electr. Insul. **2** (1995), 744–760.

[14] KOENIG, D.: Impulslose Teilentladungen in Hohlraumen von Epoxyd-harzformstoff Isolierungen, ETZ-A **90** (1969), 156–158.

[15] KOENIG, D.: Erfassung von Teilentrladungen in Hohlrauemen von Epoxyd-harzplatten zur Beurteilung des Alterungsverhaltens bei Wechselspannung, PhD Thesis, Technische Universitaet Braunschweig, Germany, 1968.

[16] BRUNING, A. M.: Design of Electrical Insulation Systems, Ph. D. Thesis, University of Missouri-Columbia, USA, 1984.

[17] BRUNING, A. M.: Private Communication, 2 May 2003.

[18] BLAIR, D. T. A.: Breakdown in Gases, from the book “Electrical Insulation”, London, U.K., Eds. Peter Peregrinus, 1983.

[19] DANIKAS, M. G.: Fast Measurements of Partial Discharges in Polyethylene Cavities with the Aid of a Subdivided Electrode Arrangement:A Study of Circuit Parameters on the Waveshape of the Detected PD Currents, J. Electr. Eng. **51** (2000), 75–80.

[20] DANIKAS, M. G.—PRIONISTIS, F. K.: Detection and Recording of Partial Discharges Below the so-called Inception Voltage, Facta Universitatis (Ser.: Elec. Energ.) **17** (2004), 99–110.

[21] KUFFEL, E.—ZAENGL, W. S.: High Voltage Engineering Fundamentals, Pergamon Press, Oxford, England, 1984.

[22] http://www.limat.ing.unibo.it/ricerca/aging_life.pdf, and the technical literature therein.

[23] BRUNING, A. M.: Private Communication, 20 October 1990.

[24] KUFFEL, E.—ZAENGL, W. S.—KUFFEL, J.: High Voltage Engineering: Fundamentals, Newnes, Oxford, England, 2000.

[25] SIDDAPPA NAIDU, K.—PRABBASHANKER, V.: Measurements of Partial Discharges — Corrections to Erroneous Counts Occurring in a Cumulative Pulse-Counting System, J. Phys. E: Sci. Intrum. **10** (1977), 1129-1132.

Received 2 May 2004
Revised 11 September 2005

Michael G. Danikas, born in 1957, Kavala, Greece, received his BSc and MSc degrees from the University of Newcastle-upon-Tyne, Department of Electrical and Electronic Engineering, England, and his PhD Degree from Queen Mary College, University of London, Department of Electrical and Electronic Engineering, England, in 1980, 1982 and 1985 respectively. From 1987 to 1989 he was a lecturer at the Eindhoven University of Technology, The Netherlands, and from 1989 to 1993 he was employed, among others, at Asea Brown Boveri, Baden, Switzerland. His research was in the fields of partial discharges, vacuum insulation, polymeric outdoor insulation, rotating machine insulation and insulating systems at cryogenic temperatures. From 1993 to 1998 he was Assistant Professor at Democritus University of Thrace, Dept. of Electrical and Computer Engineering. In 1998 he became Associate Professor in the same department. He was invited as "Maitre de conferences" at the Laboratory of Electrostatics and Dielectric Materials, CNRS, in Grenoble, France, during the summer of 1994 and as professor at the Laboratoire de Genie Electrique, CNRS, in Toulouse, France, during the summer of 1995. He spent a sabbatical from February to July 1998 at Darmstadt University of Technology, High Voltage Institute, Germany. He was invited professor at Helsinki University of Technology, High Voltage Institute, Finland, during the summer of 2002. During the academic years 1999-2001 and 2003-2004 he was Director of the Division of Energy Systems. His current research interests are breakdown in transformer oil, simulation of electrical tree propagation in polymers, study of partial discharge mechanisms in enclosed cavities, study of circuit parameters on the measured partial discharge magnitude and surface phenomena in indoor and outdoor high voltage insulators.

Nikolaos Vrakotsolis graduated from Democritus University of Thrace, Department of Electrical and Computer Engineering, in the year 2000. He carried out his diploma thesis in the Electric Energy Systems Laboratory. He pursued postgraduate studies in the same department. In his Master thesis, Mr Vrakotsolis tackled the problem of very small partial discharges in air gaps at/or below inception voltage using a non-uniform electrode arrangement.