FACTA UNIVERSITATIS (NIŠ)
SER.: ELEC. ENERG. vol. 15, No. 3, dec. 2002, 385-398

Partial Discharges in Solid Insulation Cavities: a Theoretical Analysis and a Comparison with Experimental Results

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Abstract: The deterioration of solid insulating materials is due to a significant extent to partial discharges taking place in enclosed cavities. Based on two known models, the classical capacitance model and Pedersen's model, a comparison is being made between theoretical and experimental values of partial discharges which occur in enclosed cavities. The practical consequences of such a comparison are discussed.

Keywords: Partial discharges, cavities, capacitance model, Pedersen's model, insulating materials.

1 Introduction

Partial discharges may occur in enclosed cavities of solid insulation and cause deterioration [1]. Partial discharges - if they persist - may eventually lead to ultimate failure of an insulating system. These phenomena are considered as one of the main ageing factors in solid insulating systems. Partial discharges in cavities have been studied extensively [2, 3]. In a number of previous publications [4-7], a comparison between the theoretical results obtained with the aid of the classical capacitance model and Pedersen's model and the experimental data has been carried out.

In this paper, this comparison is being extended also to experimental results of the scientific literature. In this way, the conclusions, which were

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Manuscript received January 15, 2002.

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first reported [4-7], are examined in the light of the findings of the present paper and the practical consequences drawn are discussed. It should be noted that in the context of the present paper, the terms 'initial experimental conditions' and 'non-aged conditions' are equivalent.

2 The Classical Capacitance Model and Pedersen's Model

The classical capacitance model (or abc model) represents the enclosed cavity in a solid insulation as a capacitance Cc which is in series with the neighbouring capacitance representing the next to the cavity material Cb and both of them in parallel with a capacitance which represents the rest of the material Ca (Fig. 1) [8, 9]. The capacitances C_a, C_b and C_c are designated with a, b and c respectively in Figure 1. If an a.c. voltage V_a is applied to the test specimen, another voltage V_c appears in the cavity. The relationship between the two voltages is given by

$$Vc = \frac{C_b V_a}{C_b + C_c} \tag{1}$$

From such an equivalent circuit, a relationship giving the apparent charge q of a discharge in terms of C_b is

$$q = C_b \Delta V_c \tag{2}$$

where, ΔV_c is the voltage difference between the breakdown voltage of the cavity and the voltage in the cavity after the breakdown. ΔV_c is taken to be approximately equal to V_c given the fact that the voltage in the cavity after the breakdown is taken approximately equal to zero [3].

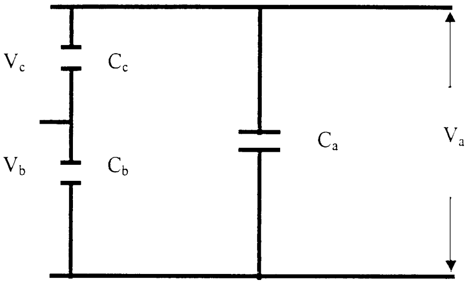

Fig. 1. The equivalent circuit according to [8] and [9].

Pedersen's model is based on the streamer criterion [10]. This model gives the induced charge q on the measuring electrode in terms of the volume of the cavity Ω, the geometrical factor of the cavity k, the difference $(E_i - E_l)$ (where E_i is the electric field for streamer inception and E_l the limiting field below which no ionization is possible), the permittivity of the surrounding insulating material in question ε_r, ε_0 the permittivity of free space ($= 8.85 \times 10^{-12}$ F/m) and $\nabla\lambda_0$ which in the case of uniform electrode arrangements is equal to the inverse of the distance between the electrodes (this function is the electric field which would occur at the cavity location - in the absence of the cavity - for a 1 V potential difference between the electrodes) [11]. Pedersen's model is expressed as follows

$$q = k\Omega\varepsilon_r\varepsilon_0(E_i - E_1)\nabla\lambda_0 \tag{3}$$

The difference $(E_i - E_l)$ is expressed by the streamer criterion, i.e.

$$E_i - E_l = \frac{BE_l}{\sqrt{2ap}} \tag{4}$$

where, $B = 8.6$ (Pa m)$^{1/2}$ (generally speaking B is a constant characteristic for the gas in the cavity, the value given above is specific for air) and $E_l/p=$ 24.2 V/Pa m for a non-attaching gas (and therefore also for air), p is the gas pressure and a is the radius of the enclosed cavity [10, 11]. For the theoretical calculations of q based on Eqs. (3) and (4), the geometrical factor k was taken from the relevant figures of [11], where k is expressed in terms of the dimensions of ellipsoids. As radius a in the case of a cylindrical cavity was taken the smaller of the axes of an equivalent ellipsoidal cavity. Based on Eqs. (1) to (4) the theoretical values of the discharge magnitude for both aforementioned models can be calculated. For convenience purposes, the theoretical values were calculated with the aid of two simple computer programmes in FORTRAN.

3 Comparison Between Experimental and Theoretical Results

All the experimental results have been taken from the scientific literature and they refer to uniform electrode arrangements.

The first comparative study refers to test specimens consisting of three sheets of polypropylene sandwiched between plane-plane electrodes [12]. The middle sheet had a cylindrical cavity. Table 1 gives the variation of the apparent charge q in terms of the diameter of the cavity whereas the thickness of the test specimen and that of the cavity remain constant.

Table 1. Results from [12]. Exp. App. Charge is the experimental apparent charge, abc charge is the chargecalculated with the aid of the classical capacitance model, Pedersen charge is the charge calculated with the aid of Pedersen's model.

Cavity diam. (mm)	Cavity thickness (μm)	Applied voltage (kV)	Specimen thickness (μm)	Exp. app. charge (pC)	abc charge (pC)	Pedersen charge (pC)
0.9	40	0.9 (±0.2)	80	61	203	70.6
2.0	40	0.9	80	126	876	336
3.2	40	0.9	80	174	2040	850

Figure 2 shows the variation of the apparent charge q (both experimental and calculated) with the diameter of the cavity.

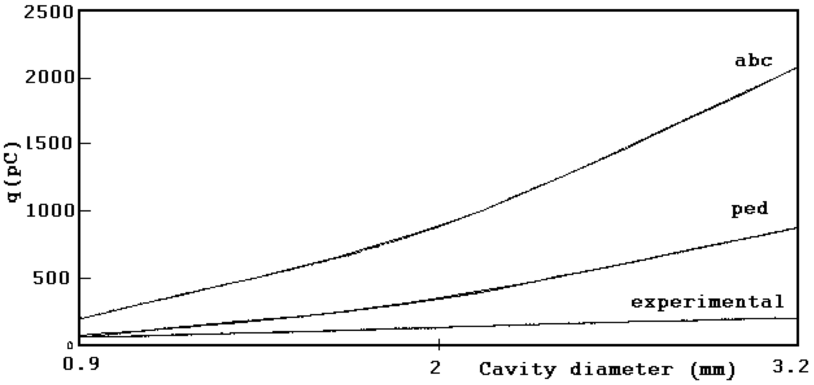

Fig. 2. Comparison between the experimental values of the charges (q) and the theoretical values of the charges derived from the abc and Pedersen's models with varying cavity diameter (cavity thickness=40 mm, specimen thickness=80 μm). In this and in all subsequent figures, exp means experimental values, abc means the theoretical values calculated with the aid of Pedersen's model.

Table 2 gives the variation of the quantities mentioned in Table 1 but with specimen thickness of 160 μm and cavity thickness of 120 μm.

Figure 3 shows the variation of the apparent charge q (experimental and calculated) with the cavity diameter.

Table 3 and Figure 4 show the results when the specimen thickness increases to 240 μm and the cavity thickness to 200 μm.

The second comparative study refers to test specimens consisting of polyethylene sheets [13]. The cavity was cylindrical. Figure 5 shows the

Table 2. Results [12]. All abbreviations in Table 1.

Cavity diam. (mm)	Cavity thickness (μm)	Applied voltage (kV)	Specimen thickness (μm)	Exp. app. charge (pC)	abc charge (pC)	Pedersen charge (pC)
0.9	120	0.9 (±0.2)	160	132	247	69.5
2.0	120	0.9	160	179	1030	309
3.2	120	0.9	160	208	2440	765

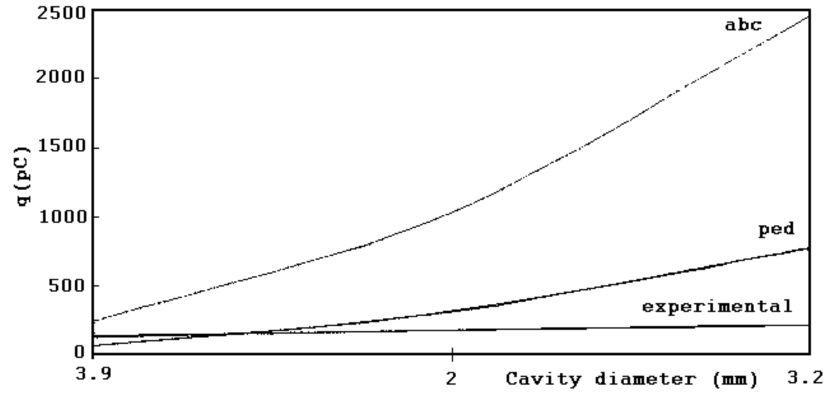

Fig. 3. Comarison berween the experimental values of the charges (q) and the theoretical values of the charges derived from the abc and Pedersen's models with varying cavity diameter (cavity thickness=120 μm, specimen thickness=160 μm.

electrode arrangement used. In this series of tests the applied voltage was calculated indirectly. Reference [14] gives only the maximum discharge inception electric field which was measured in the test specimen. From this field, the applied voltage was calculated by having multiplied the inception field with the specimen thickness.

Table 4 shows the results from [13].

Figures 6-9 offer an illustration of the results presented in Table 4. The

Table 3. Results [12]. All abbreviations in Table 1.

Cavity diam. (mm)	Cavity thickness (μm)	Applied voltage (kV)	Specimen thickness (μm)	Exp. app. charge (pC)	abc charge (pC)	Pedersen charge (pC)
0.9	200	0.9 (±0.2)	240	173	263	67
2.0	200	0.9	240	214	1130	282
3.2	200	0.9	240	219	2080	683

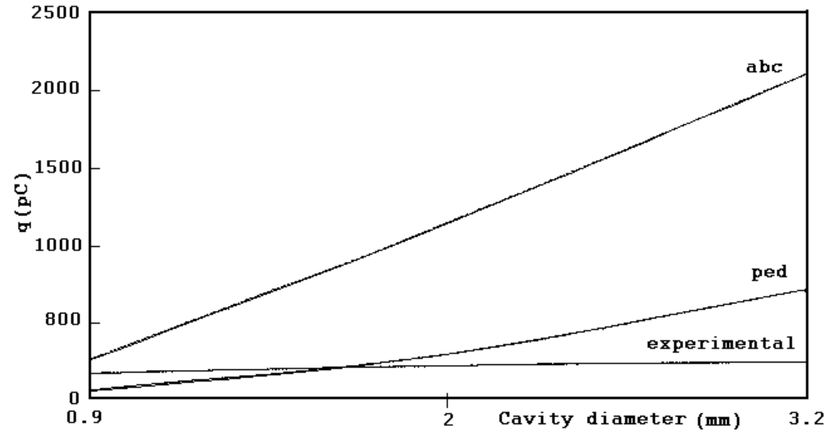

Fig. 4. Comarison berween the experimental values of the charges (q) and the theoretical values of the charges derived from the abc and Pedersen's models with varying cavity diameter (cavity thickness=200 μm, specimen thickness=240 μm.

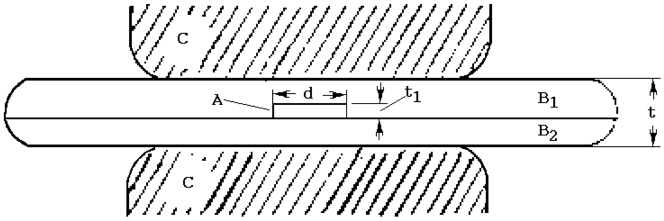

Fig. 5. The electrode arrangement (after [13]).

results of Table 4 are offered in the form of 'histograms' because the experiments were not performed under the same voltage conditions.

The third comparative study refers to test specimens made of epoxy resin [14]. The test specimens had a thickness of 5 mm with varying cavity diameter. The test voltage was 40 kV. The cavities were spherical. Table 5 shows the relevant results. Figure 10 shows the variation of the charge w.r.t. the diameter of the cavity with constant specimen thickness.

It is evident from the results presented here that Pedersen's model gives better estimates of the discharges in enclosed cavities than the classical capacitance model. It is also worth noting that with increasing cavity dimensions, the charge values (both experimental and calculated) become larger. This is to be expected considering that the charge q in the classical capac-

Table 4. Results [13]. All abbreviations in Table 1.

Cavity diam. (mm)	Cavity thickness (mm)	Specimen tickness (mm)	Applied voltages (kV)	Exp. app. charge (pC)	abc charge (pC)	Pedersen charge (pC)
0.99	0.1	0.5	8.7	3.1	7.7	3.4
1.0	0.098	1.5	9.0	4.8	69	25.3
1.04	0.1	2.0	9.3	23	120	42.7
1.02	0.101	3.0	9.3	38	285	96.1
1.0	0.095	5.0	8.9	105	735	258
0.99	0.1	10	9.2	65	3260	1060
1.03	0.297	0.5	5.6	3.1	14.3	8.9
1.01	0.312	0.75	6.2	22	39.6	17.5
1.05	0.301	1.0	6.6	3.5	65.6	25.7
1.05	0.292	1.5	5.6	46	122	49.9
1.01	0.296	3.0	5.7	155	543	183
1.01	0.303	5.0	5.4	250	1480	486
1.02	0.301	10	5.5	150	5810	1830

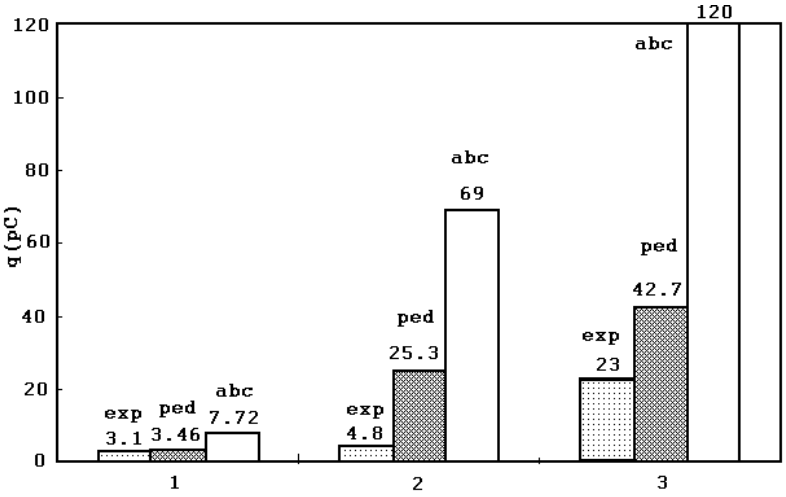

Fig. 6. Comparison of the experimental value of the charge (q) with the theoretical values derived from the abc and Pedersen's models (see Table 4).

itance model increases proportionally with the surface area of the cavity whereas in Pedersen's model it increases proportionally with the volume of the cavity.

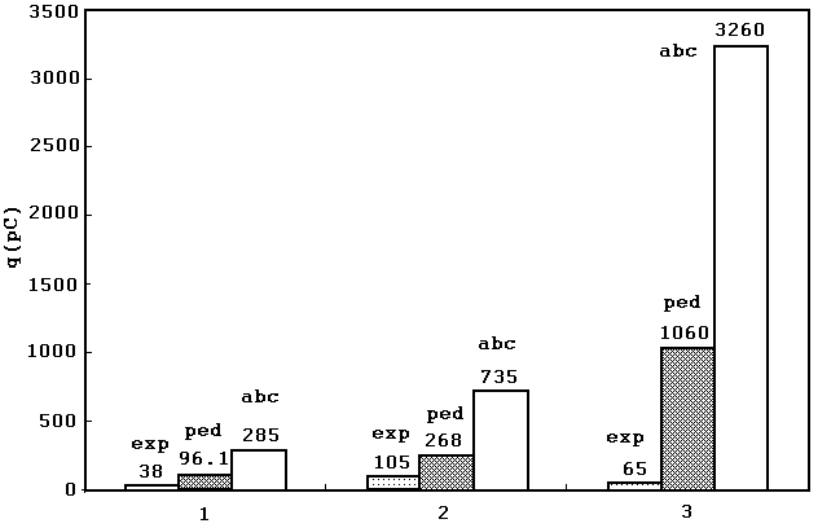

Fig. 7. Comparison of the experimental value of the charge (q) with the theoretical values derived from the abc and Pedersen's models (see Table 4).

Table 5. Results [14]. All abbreviations in Table 1.

Cavity diam. (mm)	Specimen tickness (mm)	Applied voltages (kV)	Exp. app. charge (pC)	abc charge (pC)	Pedersen charge (pC)
1.4	5	40	100	369	53.7
1.8	5	40	190	780	101
2.2	5	40	400	1460	166
2.6	5	40	700	2550	252
3.0	5	40	1100	4290	361
3.4	5	40	1650	7190	493

4 Discussion, Practical Consequences and Suggestions for Further Research

The present paper comes as a continuation of a research which spanned over several years regarding the applicability of the classical capacitance and Pedersen's models for non-aged conditions [4-7, 15]. Experimental work performed by one of the authors (MGD) and his colleagues over several years showed that Pedersen's model can better predict the discharge magnitudes in enclosed cavities than the capacitance model. This implies that - at least initially - we have the presence of the streamer mechanism in enclosed cavities. The results of this paper - which are taken exclusively from the

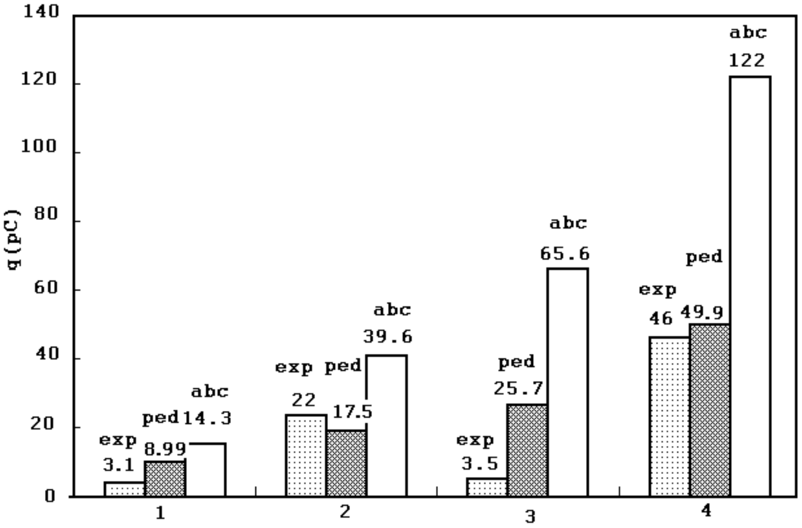

Fig. 8. Comparison of the experimental value of the charge (q) with the theoretical values derived from the abc and Pedersen's models (see Table 4).

scientific literature - tend to confirm the conclusions of [4-7, 15]. A physical interpretation of the predominance of the streamer mechanism in enclosed cavities can be given: Townsend's second ionization coefficient γ takes very small values in an enclosed cavity precisely because the cavity does not come into contact with any metallic surface [16].

It must, however, be noted that there are strong indications that Pedersen's model performs better than the classical capacitance model only for initial experimental conditions. The results presented in [4-7, 15] and in the present paper refer to initial experimental conditions. Whether Pedersen's model still performs better when we have aged test specimens is uncertain, given also the evidence of [17], according to which for initial experimental conditions the streamer discharge mechanism prevails whereas in aged conditions there is a predominance of the Townsend mechanism.

The predominance - for initial experimental conditions - of the streamer mechanism was shown in [18, 19], where the waveforms of the discharge currents in enclosed cavities were observed to have very steep rise times (in the order of 1 nsec). The practical consequences of this discussion are that very fast discharge events are to be expected with the switching on of the high voltage (provided that the inception field for discharges has been reached) and that appropriate discharge detectors (with the capability of detecting events of rise time in the range of 1 nsec) should be used.

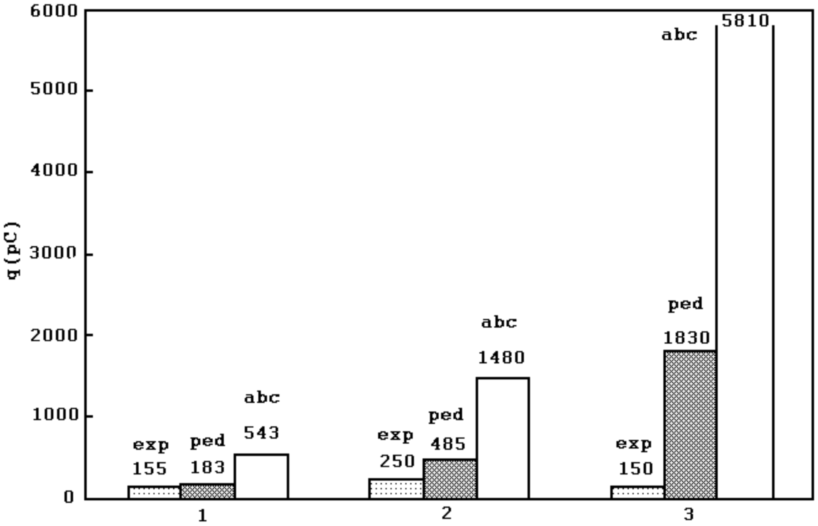

Fig. 9. Comparison of the experimental value of the charge (q) with the theoretical values derived from the abc and Pedersen's models (see Table 4).

The results presented here - with the exception of Kuebler's data [14] - show that the calculated charges (both from the classical capacitance and Pedersen models) is larger than the experimental charges. There is an increasing divergence between the calculated charge values and the experimental ones with increasing cavity dimensions. This is due to the fact that - for both models - it is assumed that the whole of the cavity is discharged. In reality, this assumption may not be necessarily true. Especially for Pedersen's model, that was a point of criticism in a discussion published several years ago [20]. The divergence between experimental and theoretical charge values may also be due to recombination effects, especially if space charges exist [3].

Work which has to be carried out in this field concerns the application of both models to aged conditions. Since there is still some conflicting evidence as to whether streamer discharges transform to Townsend ones [21, 22], it would be interesting to investigate whether the aforementioned models apply in aged conditions and to what extent.

Further work envisaged regarding Pedersen's model would be in practical applications. It has been shown until now that this model can give reasonable estimates in laboratory conditions. It is true that the aforementioned model includes a variety of parameters, and in this respect, it is better than the classical capacitance model. Its validity, however, has not been proved

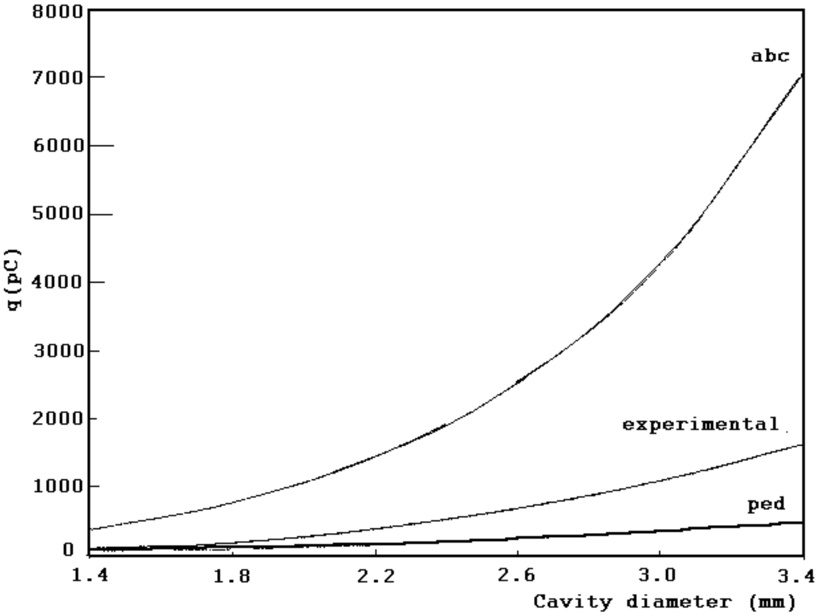

Fig. 10. Comparison of the experimental value of the charge (q) with the theoretical values derived from the abc and Pedersen's models with varying cavity diameter (specimen thickness=5 mm).

for practical applications. Pedersen' model assumes that the gas in an enclosed cavity is 'air-like'. This assumption has to be tested, especially in the light of more recent research regarding the gases in cavities and their pressure variation [23]. Pedersen's model has also to be further tested under conditions of elevated temperature and humidity (i.e. other than normal) since there is evidence that these parameters influence to a significant extent the behaviour of streamer discharges [24-26]. A better modelling of the discharge phenomena inside enclosed cavities should be sought, taking into account the physical processes inside the cavities. As things stand for the time being, no consideration is given to the modelling of the very small partial discharges which are considered as a 'silent' stage of discharge development ('silent' exactly because it is difficult to be detected by conventional means) but which may cause deterioration of the insulating material [27].

Another possible area of research is the study of the transition from cavity discharge to electrical treeing with the aid of Pedersen's model. What sort of discharges cause electrical treeing? Are they more of the streamer or of the Townsend type or both? Is there a critical discharge magnitude causing the initiation of electrical tree from a cavity and what is its relation to other experimental parameters, such as gas pressure and inner wall chemistry? Trees emanating from cavities were shown both experimentally [7, 28] and theoretically by simulation tools [29]. Needless to say that questions as those are still pending and in great need of an answer [30].

5 Conclusions

In this paper, a comparative study between the classical capacitance model and Pedersen's model has been made. It seems that Pedersen's model is more appropriate than the capacitance model in order to estimate discharge magnitudes at least for initial conditions. Based on the findings of the present paper, one may say that it seems that, initially, streamer discharges are prevalent. Questions as to the applicability of Pedersen's model in aged conditions have been risen and are in need of an answer.

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