Journal of ELECTRICAL ENGINEERING, VOL. 52, NO. 5-6, 2001, 166–170

COMMUNICATIONS

THE CASE OF PEDERSEN'S THEORY TO MODEL PARTIAL DISCHARGES IN CAVITIES ENCLOSED IN SOLID INSULATION: A CRITICISM OF SOME OF ITS ASPECTS FROM AN ELECTRICAL ENGINEERS' AND FROM A PHYSICISTS' POINT OF VIEW

Michael G. Danikas - George E. Vardakis *

Pedersen's model is a model tackling the problem of partial discharges in solid insulation cavities. The aforementioned model is deduced with the help of the electromagnetic theory and not with the aid of an equivalent capacitance circuit, as is the case for the abc model (called also capacitance or Gemant-von Phillippoff model). Based on some experimental data, it is the aim of this paper to critically examine some aspects of Pedersen's model from an electrical engineers' point of view.Aspects of Pedersen's model are also studied and discussed from a physicists' point of view. Future research plans are outlined.

K e y w o r d s: partial discharges, cavities, capacitance circuit, Pedersen's model, streamer criterion

1 INTRODUCTION

Partial discharges (PD) play a dominant role in determining - among other factors - the lifetime of a solid insulation and/or of a system consisting of solid/liquid/gaseous components [1-3]. Numerous studies have been carried out regarding the types of PD, their relation to insulation damage, the methods of PD detection, their effect on the insulation lifetime and their modelling [4-13].

Pedersen's model [13] tackles the problem of discharges in cavities enclosed in solid insulation using the electromagnetic theory and not the capacitance modelling of previous research [11, 12]. Pedersen's paper proposes a model based on the concept of induced charge, *ie*the charge induced at the electrode terminals of the system. Pedersen's model has been extensively investigated in numerous publications. It has also been compared to the more traditional abc capacitance model proposed quite early by Gemant and von Philippoff [14-18].

It is the aim of this paper to investigate some aspects of Pedersen's model. The detailed theory of the said model will not be given here, only pertinent to our criticism equations and parts of [13] will be commented upon. Particular emphasis will be given to previous experimental results obtained by one of the authors (MGD). The thoughts and arguments which will be developed in the context of this paper will be based both on an electrical engineers' and a physicists' point of view. By doing that, we hope to give a more complete picture of the aforementioned model.

2 PEDERSEN'S MODEL

The model is based on electromagnetic theory. It quantifies the relationship between partial discharge transients and the creation (or changes) of charge distribution in the inter-electrode space, changes which might result from a partial discharge. In trying to do that, the model considers the relationship between the induced charge on the electrodes and the measured transients as well as the relationship between space charges and the induced charge on the electrodes [13, 18, 19]. A detailed account of the model will not be given here. The interested reader may consult references [13, 19] for an analytical account of Pedersen's work. Here, only the final equation will be given, an equation relating the charge q induced on the measuring electrode by the partial discharge in a cavity to the cavity geometric factor k, the cavity volume Ω, the inception electric field for streamer inception E_i, the limiting electric field for ionization E_l, the relative permittivity of the surrounding solid insulating material ε_r, the permittivity of free space ε_0, and $|\vec{\nabla}\lambda_0|$, the function which gives the ratio of the electric field at the position of the cavity (in the absence of a cavity) to the voltage between the electrodes [20], *ie*

$$q = k\Omega\varepsilon_r\varepsilon_0(E_i - E_l)|\vec{\nabla}\lambda_0| \tag{1}$$

One further comment about the function $|\vec{\nabla}\lambda_0|$: this function is the electric field which would occur at the cavity location (in the absence of a cavity) for a 1 V potential difference between the electrodes. For plane-plane electrode geometry, for example, the function $|\vec{\nabla}\lambda_0|$

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

ISSN 1335-3632

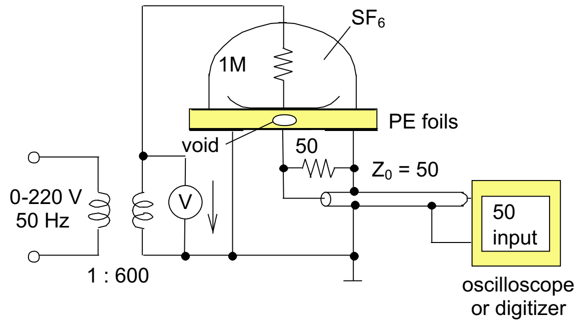

Fig. 1. Subdivided electrode arrangement for the study of PD currents in polyethylene cavities.

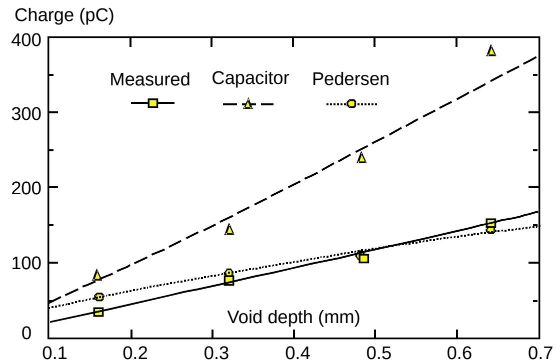

Fig. 2. Experimental and theoretical PD values with varying cavity thickness. Fixed diameter of 2 mm.

would be $1/d$ (d being the distance between the plane-plane electrodes) whereas for coaxial cylindrical electrodes $|\vec{\nabla}\lambda_0|$ would be $1/[r\ln(R_0/R_i)]$ (where R_0 is the outer cylinder radius, R_i is the inner cylinder radius and r the radius of the point at which the electric filed is being calculated) [20].

It should further be noted that $\vec{\nabla}\lambda = h\,\vec{\nabla}\lambda_0$, where h is a parameter depending on the cavity geometric factor k and the relative permittivity of the bulk of the dielectric [13]. We will analyze the parameter λ below.

The quantity $(E_i - E_l)$ is calculated in terms of the streamer criterion, *ie*

$$\frac{E_i}{p} = \left(1 + \frac{B}{\sqrt{2ap}}\right)\frac{E_l}{p} \qquad (2)$$

where, B is a constant characteristic for the gas in the cavity $B = 8.6\,(m\cdot Pa)^{1/2}$ for air), a is the radius of the cavity and p is the pressure in the cavity. The merit of Eq. (1) is that the charge q is related to a variety of parameters which influence indeed the discharge behaviour in a cavity. The introduction of so many parameters is especially welcome if one thinks that the traditional capacitance abc model [11, 12] does not take into account parameters such as cavity pressure, cavity volume, cavity geometric factor *etc*. Another complex treatment taking into account elasticity of the dielectric media was outlined in [21].

It is evident that Pedersen's model is based on the streamer criterion and consequently it can calculate and/or predict discharges of the streamer type. This leaves of course entire categories of discharges such as PD of Townsend type and the so-called swarming micro-discharges outside the interpretational capabilities of the model examined here.

2.1 Experimental Arrangement and Results: Pedersen's Model from an Electrical Engineer's Point of View

The experimental set-up for the study of PD in cavities is shown in Fig. 1. This set-up gives the possibility to register fast PD events with the aid of a digitizer up to 1 GHz bandwidth. Polyethylene sheets, each of 0.16 mm thickness were used, up to a thickness of seven sheets. A cylindrical cavity was established in the middle of the sample. The voltage applied was 4 kV at 50 Hz. Further details about the experimental arrangements can be found in [14, 22-25].

Regarding Fig. 1 and the experimental arrangement used, we have to note that SF6 was used in order to avoid surface discharges. The said gas, however, was not allowed to permeate into the enclosed cavity and consequently the gas inside the enclosed cavity was assumed to be air. In Fig. 2 experimental and theoretical (calculated from Eq. (1)) discharge values are presented. Cavities with a fixed diameter of 2 mm and of various thicknesses (in Fig. 2 cavity thickness is denoted with void depth) are investigated. Given the fact that the discharge mechanism is a phenomenon of statistical nature, we see a very good agreement between experimental and theoretical PD values.

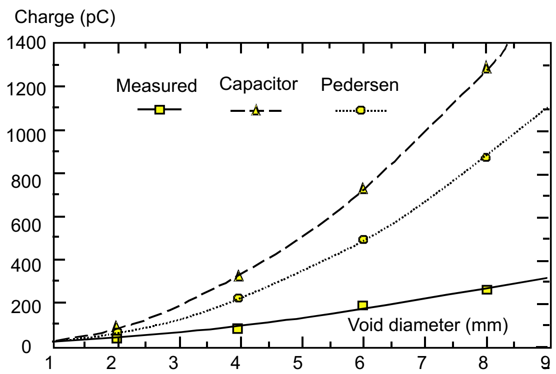

Fig. 3. Experimental and theoretical PD values with varying cavity diameter. Cavity thickness of 0.16 mm.

In general, we can say that, given the rather small difference between experimental and theoretical values, Pedersen's model works well for the range of thicknesses examined.

In both Figs. 2 and 3 the theoretical curve resulting from the capacitor (or abc or Gemant-von Phillippoff) model is also shown. In Fig. 3 experimental and theoretical PD values are given with varying cavity diameter and with cavity thickness fixed at 0.16 mm. It is seen that there is an increasing deviation between experimental and theoretical values as the cavity diameter increases. This may be due to the difference $(E_i - E_l)$. However, given that this difference should be constant (since the thickness of the cavity remains the same, *ie* 0.16 mm), one may assume that the quantity that changes is the pressure inside the cavity. It is possible that inside the cavity there is not simply - as is assumed - air but also gaseous byproducts of the discharges (byproducts other than gaseous, of course, should not be excluded). Such byproducts may have (or may cause) a lower dielectric strength and consequently the experimental results are lower than the theoretical ones.

Another reason for the discrepancy between experimental and theoretical values may also be the fact that Eq. (2) assumes a breakdown in a uniform field gap. However, cavity PD are not in the strict sense breakdown events but rather events leading to a redistribution of charges on the surface of the cavity. Consequently, PD may result from conditions which will be rather insufficient for a breakdown event. Moreover, there are various types of discharges, for example, sustained discharges and non-sustained discharges. Pedersen's model formulates the difference $(E_i - E_l)$ according to Eq. (2) and does not take into account the possibility of occurrence of non-sustained PD. Since the role of non-sustained discharges is not clear as yet with respect to the damage caused in the insulation and also to its lifetime, it is evident that more work has to be done on these issues before one may draw any definite conclusions about Pedersen's model. What would have been an even more exciting prospect would be the testing the validity of Pedersen's model in the voltage regime just below the so-called inception voltage, where there have been a number of reports about possible damage to the insulation because of some discharge activity not well detected by conventional PD detectors [26-28].

The above criticism should not make one think that Pedersen's model is not a useful tool in calculating the magnitude of PD in cavities. It is indeed a very useful tool, a tool that gives a better estimate of PD magnitude in enclosed cavities than the traditional abc capacitance model. The validity of the latter sentence has been amply demonstrated in a series of publications [14, 16, 17]. Regarding its ability to give scaling law relationships [16], Pedersen's model has proved to be of equal value with the traditional abc capacitance model [29].

2.2 Pedersen's Model from a Physicist's Point of View

In this chapter we will examine the said model from the point of view of a physicist. Our aim here is to point out some aspects of the model which may pose some further questions. It is not our aim either to give an answer to the questions we pose or to propose any improvements of the above model. In this chapter we will cite Pedersen's view (from [13]) together with our view.

According to [13], "...the induced charge related to the charge distribution on S (S being the surface of the cavity) can be expressed in the form

$$q = -\int_S \lambda \sigma \mathrm{d}S \tag{3}$$

in which λ is a dimensionless scalar function which depends on the position of $\mathrm{d}S$ only". A criticism which can be raised against Pedersen and his colleagues is that although λ is a quantity which is used throughout [13], there is no clear definition that λ is generally a kind of electrostatic potential. Solving Laplace's equation for the electrostatic potential V, with the same boundary conditions (except the values boundary conditions 0 and 1 at the electrodes) we have almost the same "formation" for both λ and V. As is shown in [13] $\lambda = \frac{V}{U}$ and it is clear that we take λ calculating the potential V and dividing with the voltage U. It seems that λ is not a function without physical meaning, but it is the relative potential and can be expressed in terms of a percentage. It is not an arbitrarily inserted function as it is seemed to be in the introduction of [13], but its existence can be justified from the following need of the dipole moment to be divided by the distance in order to calculate the charge.

In [13] the notion of the electric dipole is introduced because "...the net charge within the void remains zero". The question here is whether one has the right to use equations and the formalism from the electric dipole since the latter presupposes the existence of charges (positive and negative) at a certain distance l between them. In addition to this, considering that discharges are "small" currents, which may lead, under certain circumstances to charge build-up and to tree inception, we may conclude that the net charge within the void is not always zero. Nobody can be sure that inside the void, charge dynamics will give zero total charge. Of course, byproducts enhance the existence of such currents. Furthermore, in [13] it is stated that "the dipole moment μ of the charge deposited on S is given by

$$\vec{\mu} = \int_S \vec{r} \sigma \mathrm{d}S \tag{4}$$

where $\vec{r}$ is a radius vector which locates the position of the surface element $\mathrm{d}S$". The definition of (electric) dipole moment can be changed as shown below:

$$\vec{\mu} = \int_S \vec{a}(\vec{r}) \sigma(\vec{r}) \mathrm{d}S \tag{5}$$

where $a(\vec{r})$ is the thickness of the charged layer. This will calculate more accurately the induced charge inside the voids because the induced charge should not be considered as purely surface phenomenon.

It is evident from the above that the criticism - regarding some of the physics of the model - refers to problems of definitions. Some aspects of Pedersen's model need further clarification. Having said that, it must be pointed that Pedersen's model is a useful tool in approaching the question of PD in enclosed cavities. In a research field, where very often approximations of the order of magnitude are deemed to be satisfactory, Pedersen's model obtains on many occasions close agreement between experimental and theoretical data.

3 PROPOSALS FOR FURTHER RESEARCH

Experimental results on PD in enclosed cavities have been obtained until now with more or less standard cavity shapes (*ie*cylindrical [14, 15], spheroidal [17, 18]). It would be challenging to try to test Pedersen's model ability to estimate and/or predict PD magnitudes in cavities of rather irregular shape in laboratory conditions (we may calculate approximately the geometric factor of irregular shape cavities with the aid of Pedersen's figures on k taken from [13]). Such an approach - if successful - would add to the claims of the said model.

Furthermore, Pedersen's model should be tested with real insulating systems. Tests with spacers, cables with solid insulation etc. should be undertaken. It is only in the real world that we can see whether the aforementioned model is truly valid. Of course, one of the main problems to be faced with this kind of tests is that in an industrial insulation, not one but many cavities may be active at the same time creating thus a multitude of PD patterns [30]. It is our proposal that, in this case, Pedersen's model should be tested against the largest registered PD magnitude. The reason for this is that Pedersen's model is not adequate to describe a train of PD pulses but only a single PD pulse.

Pedersen' model should be tested also with aged samples. What was presented in the previous chapter were experimental results with non-aged samples. Is Pedersen's model adequate also for aged conditions? We tend to think - for reasons explained above and having to do with the production of gaseous byproducts in aged cavities - that this is not the case but it remains to be seen whether our conjecture is correct.

A further area of work would be the close monitoring of the nature of the developing gaseous byproducts inside a cavity under discharge conditions. Such information would give us the opportunity to study in more detail whether the difference $(E_i - E_l)$ is adequately expressed by Eq. (2). Steps in this direction have been made in [31] where gas analysis of the cavity was performed with the aid of gas chromatography (GC). However, the research direction in [31] was towards the study of multi-factor ageing and not the study of PD in conjunction with Pedersen's model.

Finally, the transition from cavity discharge to electrical treeing could be studied with the aid of Pedersen's model. The critical PD magnitude causing the initiation of treeing from a cavity merits particular interest and can be studied with the said model. Experimental work on this matter could be carried out with spherical cavities (or indeed any other cavity shape) which - as has been shown - are capable of producing treeing structures [17, 32, 33].

4 CONCLUSIONS

In this paper Pedersen's model was critically examined. In our view, the said model, in the range of cavity dimensions investigated, seems to give rather reasonable estimates. Such estimates seem to agree better with practical results with the smaller cavity dimensions. Certain questions - in need of further clarification - regarding Pedersen's model arise from the use of some formulae and the definition of the function λ.

References

[1] KELEN, A.: Studies on Partial Discharges on Solid Dielectrics - a Contribution to the Discharge Resistance Testing of Insulating Materials, Acta Polyt. Scand. 16 (1967), total number of pages: 138.

[2] MASON, J. H.: Discharges, IEEE Trans. Electr. Insul. 13 (1978), 211-238.

[3] DEVINS, J. C.: The Physics of Partial Discharges in Solid Dielectrics, IEEE Trans. Electr. Insul. 19 (1984), 475-495.

[4] IEEPROC. SCI., MEAS.—TECHNOL.: 142 no.1 (1995), Special Issue on Partial Discharges (the whole issue).

[5] DANIKAS, M. G.: The Definitions Used for Partial Discharge Phenomena, IEEE Trans. Electr. Insul. 28 (1993),1075-1081.

[6] DANIKAS, M. G.: Small Partial Discharges and their Role in Insulation Deterioration, IEEE Trans. Diel. Electr. Insul. 4 (1997), 863-867.

[7] HOLBOLL, J. T.—BRAUN, J. M.—FUJIMOTO, N.—STONE, G. C.: Partial Discharges in Flat, IEE Proc.-Sci. Meas. Technol. 142 (1995),490-494.

[8] VANBRUNT, R. J.—CERNYAR, E. W.: System for Measuring Conditional Amplitude Phase, or Time Distributions of Pulsating Phenomena, J. Reas. of the Nat. Inst. Stand. Technol. 97(1992), 635-671.

[9] KENIG, D.—NARAYANARAOY.: Teilentladungen in Betriebsmitteln der Energietechnik, Berlin: vde, (1993).

[10] ENGEL, K.: Bewertung von Teilentladungen in spaltfoermigen Isolierstoffdefekten, Diss., Universitaet Dortmund, Dortmund, Germany, 1998.

[11] GEMANT, A.: Die verlustkurve lufthaeltiger Isolierstoffe, Z. Tech. Phys. 13 (1932), 84-189.

[12] GEMANT, A.—PHILIPPOFF, W. V.: Die Funkenstrecke mit Vorkondensator, Z. Tech. Phys. 13 (1932), 425-430.

[13] CRICHTON, G. C.—KARLSSON, P. W.—PEDERSEN, A.: Partial Discharges in Ellipsoidal and Spheroidal Voids, IEEE Trans. Electr. Insul. 24 (1989), 335-342.

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

[15] BRUNING, A. M.—DANIKAS, M. G.: Observations on Discharges Above and BelowCIV in Polymer Insulation, Ann. Rep. Conf. Electr. Insul. Diel. Phen., Knoxville, USA, 1991, 638-647.

[16] DANIKAS, M. G.: Some possible New Applications of a partial Discharge (PD)Model and its Relation to PD Detection Sensitivity, Eur. Trans. Electr. Power 6 (1996), 445-448.

[17] DANIKAS, M. G.—ADAMIDIS, G.: Partial Discharges in Epoxy Resin Voids and the Interpretational Possibilities and Limitations of Pedersen's Model, Archiv f. Elektrot. 80 (1997), 105-110.

[18] HOLBOLL, J. T.: The Resistance of Composite Materials Against Electrical Discharges - Partial Discharges in Voids in Epoxy Plastic, Diss., Technical University of Denmark, 1992.

[19] PEDERSEN, A.—CRICHTON, G. C.—MCALLISTER, I. W.: The Theory and Measurement of Partial Discharge Transients, IEEE Trans. Electr. Insul. 26 (1991), 487-497.

[20] BOGGS, S. A.: Partial Discharge - Part III: Cavity-Induced PD in Solid Dielectrics, IEEE Electr. Insul. Mag. 6 (1990), no. 6, 11-20.

[21] MARTON, K.—KOLLÁR, M.—GARGUŠOVÁ, M.: Pressure and Tensile Stress in Gas Filled Cavity in Insulating during Partial Discharge Activity, J. Electr. Eng. **48 (1997)**, 281-286.

[22] DANIKAS, M. G.: Study of Partial Discharges in Polyethylene Voids, Proc. 6th BEAMA Int. Electr. Insul. Conf., Brighton, UK, 1990, 286-290.

[23] DANIKAS, M. G.: Discharge Studies in Solid Insulation Voids, Ann. Rep. Conf. Electr. Insul. Diel. Phen., Pocono Manor, USA 28-31, 1990, 249-254.

[24] DANIKAS, M. G.: Discharges in Polymers, Proc. 3rd Int. Conf. Polym. Insul. Cables (JICABLE 91), Versailles, France, 1991, 267-271.

[25] DANIKAS, M. G.: Some Further Comments on the Fast Meaurements of Partial Discharges in Polyethylene Voids, Proc. 20th Electr. Electron. Insul. Conf., Boston, USA, 1991, 220-224.

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

[27] TURNER, N. H.—BRUNING, A. M.: Analysis of Electrical Insulator Surfaces by X-ray Photoelectron Spectroscopy, IEEE Trans. Diel. Electr. Insul. 2 (1995), 1140-1146.

[28] LINZEY, W. G.—TURNER, N. H.—BRUNING, A. M.—BERNSTEIN, B. S.: Correlation of the Thermal History and Level of Oxidation with Field Failure in a Primary Distribution Cable Study, Conf. Rec. 1998 IEEE Int. Symp. Electr. Insul., Arlington, Virginia, USA, 1998 , 105-108.

[29] DANIKAS, M. G.: Some New Relationships and a Scaling Law Regarding Partial Discharges in Spherical Cavities Enclosed in Solid Insulation, Acta Electroteh. Napoc. 39 (1998), 5-9.

[30] DANIKAS, M. G. CHENG,—F. C: Discussion on Thickness Determination of Polymeric Power Cables, IEEE Trans. Diel. Electr. Insul. 2 (1995), 1161-1165.

[31] GJAERDE, A. C.: Multi-Factor Ageing of Epoxy - The Combined Effect of Temperature and Partial Discharges, Diss., Norwegian Institute of Technology, Trondheim, Norway, 1994.

[32] DANIKAS, M. G.—KARAFYLLIDIS, I.—THANAILAKIS, A.—BRUNING, A. M.: Simulation of Electrical Tree Growth in Solid Dielectrics Containing Voids of Arbitrary Shape, Model. Simul. Mater. Sci. Eng. 4 (1996), 535-552.

[33] KARAFYLLIDIS, I.—DANIKAS, M. G.—THANAILAKIS, A.—BRUNING, A. M.: Simulation of Electrical Tree Growth in Solid Insulating Materials, Arch. f. Elektr. 81 (1998), 183-192.

Received 31 October 2000

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 at Asea Brown Boveri, Baden, Switzerland. He researched 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, Department of Electrical and Computer Engineering. In 1998 he became Associate Professor in the same department. During the academic years 1999-2000 was elected director of the Division of Energy Systems. He was reelected director for the academic year 2000-2001. His current research interests are breakdown in transformer oil, simulation of electrical treeing 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 hv insulators.

George E. Vardakis was born in 1972. He received his BSc degree in Physics from Aristotle University of Thessaloniki, Greece. He is currently doing research leading to a PhD in the field of High Voltage Engineering and Insulating Materials at Democritus University of Thrace, Xanthi, Greece. His current research interests are electrical trees in solid insulating materials, simulation of electrical trees and partial discharge mechanisms.