Journal of International Scientific Publications:
Materials, Methods & Technologies, Volume 5, Part 2
ISSN 1313-2539, Published at: http://www.science-journals.eu

INFLUENCE OF WATER TREES ON BREAKDOWN VOLTAGE OF POLYMERIC CABLES INSULATIONS

Cristina Stancu[1], Petru V. Notingher[2],
Mihai Gabriel Plopeanu[2]
[1]INCDIE ICPE CA, 313 Splaiul Unirii, Bucharest, Romania
[2]Politehnica University of Bucharest, 313 Splaiul Independentei, Bucharest, Romania

Abstract

In a previous paper was shown that water trees development modifies considerably the electric field repartition, which increases significantly in the vicinity of treed areas. In order to find the water trees influence on the breakdown voltage, in the present paper, an experimental study on model cables insulated with low density polyethylene is done. In insulation samples, water trees with various dimensions and densities were developed. For the reduction of the test duration, an electric field with a higher frequency (3-5 kHz) was used. For breakdown voltage measurement an automatic setup was realized.

For each value of the ageing time the dimensions and densities of water trees and breakdown voltage were measured and the dependency of the breakdown voltage with these quantities were analysed.

The results show a significant reduction of the breakdown voltage of treed cables insulations compared to un-treed ones.

Key words: *polyethylene, water treeing, electric field, breakdown, power cables*

1. INTRODUCTION

The initiation and the development of water trees in polymeric insulations are very complex phenomena. Many simplified models were proposed in order to explain water treeing phenomenon (Steennis et all, 1990, Ross et all, 1993, Notingher et all, 2005) but until now, no general model was elaborated (Notingher et all, 2005). Some of these models consider that the local values of the electric field intensity at the interface water needle – dielectric or on the water tree front play an essential role in the initiation and/or the propagation of water trees (Filippini et all, 1998).

The water trees shape and dimensions obtained both on laboratory specimens (by accelerated experiments), and on cables (in laboratories or in their operation) depend on various factors. Among these factors one can emphasizes the type of samples, the nature and the structure of the material, and the environment stresses (humidity, oxygen, radiations, temperature, electric field, mechanical stress etc.) (Notingher et all, 1996, Notingher et all, 1998, Dissado et all, 1992, Ciuprina et all, 2004, Filippini et all, 1998, Radu, 1997, Stancu, 2008, Notingher et all, 2010).

The usual methods to grow water trees in an accelerated manner under laboratory conditions are the needle-plane or needle-needle method (Filippini et all, 1988, Notingher et all, 1996, Notingher et all, 1998, Dissado et all, 1992, Ciuprina et all, 2004, Filippini et all, 1998, Radu, 1997), flat samples method (Stancu, 2008, Notingher et all, 2010, Ciuprina et all, 2003) and cylindrical samples method (Stancu, 2008, Stancu et all, 2008). If with the first methods, generally vented trees are obtained (Figs. 1 (Radu, 1997) and 2 (Notingher et all, 2010)), by using the third method vented trees (Fig. 3.a) as well as bow tie trees (Fig. 3.b) (Stancu, 2008, Stancu et all, 2008) can be obtained.

Fig. 1. Water trees in a low density polyethylene needle-plan sample: 1 – water needle; 2 – water trees ($U = 3$ kV, $f = 13$ kHz, $r_0 = 5$ μm, $\tau = 250$ h).

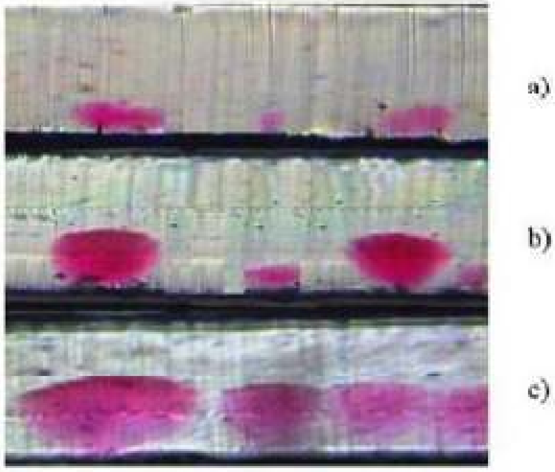
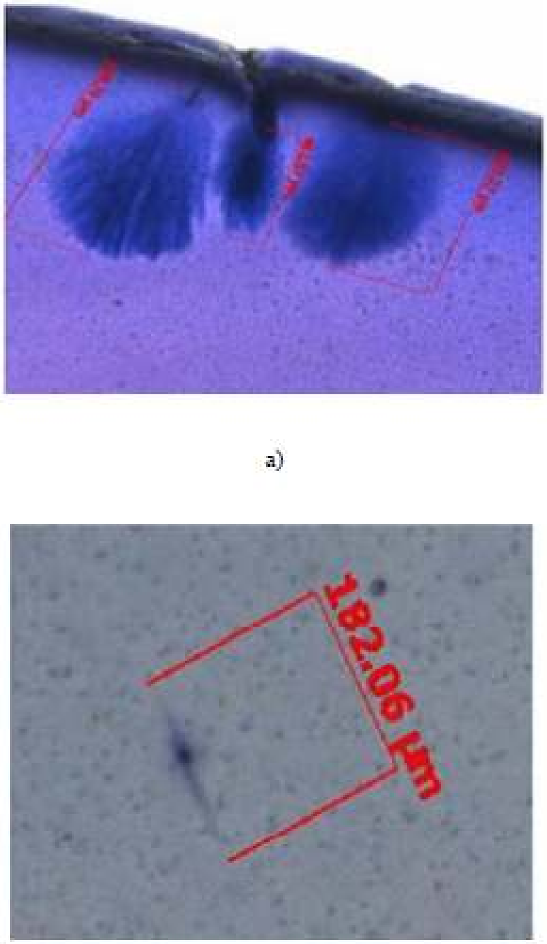


Fig. 2. Water trees in low density polyethylene plane samples taken from the insulation of a high voltage cable for different values of ageing time τ: a) $\tau = 48$h b) $\tau = 72$h c) $\tau = 96$h ($E = 4$ kV/mm, $f = 5$ kHz).



a)

b)

Fig. 3. Vented trees (a) and bow tie trees (b) developed in a low density polyethylene insulation of a medium voltage cable (U = 17 kV, f = 3 kHz, τ = 456 h).

The development of water trees determines significant modifications of dielectric properties of insulations. Thus, resistivity and electrical strength decrease, while electrical permittivity and dielectric losses (respectively the loss factor) increase (Radu, 1997, Stancu, 2008, Notingher et all, 2010, Ciuprina et all, 2003, Notingher et all, 2010, Nakamura et all, 2001, Hai, 2006).

On the other hand, because in treed areas the electrical permittivity can take values up to 3-4 times higher than in un-treed areas (Radu et all, 1996), in the water trees vicinity (outside of water trees) the electric field greatly intensifies (Notingher et all, 1995, Notingher et all, 2000, Notingher et all, 2000, Radu et all, 1997, Radu et all, 2000, Acedo et all, 2001, Stancu et all, 2009, Stancu et all, 2009). This increase is emphasized by the ionic space charge related to water trees (Visata et all, 2001) and contributes to the decrease of partial discharge and electrical trees inception voltage (Fig. 4) (Notingher, 2005, Radu, 1997, Stancu, 2008, Stancu et all, 2009). As a consequence, the breakdown of cables insulation may appear for lower applied voltage values (Hai, 2006, Stancu et all, 2009).

Furthermore, the electrical degradation of insulations may continue even after the voltage is switched off, due to the residual electric fields generated by the space charge related to water trees (Stancu et all, 2010).

Fig. 4. Electrical tree inception in front of a water tree one.

In the present paper the results of a study concerning the influence of dimensions and water trees density on the breakdown voltage values of polymeric insulated cables are presented. In order to develop water trees in an accelerated manner a new method was created. Water trees with different dimensions in polyethylene insulated model cables were developed. Then, the water trees dimensions and density were measured as well as the breakdown voltage for treed and un-treed samples.

2. ELECTRIC FIELD REPARTITION

Computation of the electric field in the absence and in the presence of water trees and space charge was done for the models corresponding to the three types of samples, respectively needle-plan, plane and cylindrical samples. In all cases the electrostatic regime of the electric field was considered by satisfying the electric flux law:

$$\mathrm{div}\ D = \rho_v \tag{1}$$

and the electrostatic potential law

$$E = -\ \mathrm{grad}\ V, \tag{2}$$

where $D = \varepsilon_0 \varepsilon_r E$ represents the electrical induction, ρ_v – volume density of the electric charge, E – electric field strength, V – electric potential, $\varepsilon_0 = 8.85.10^{-12}$ F/m – absolute permittivity of vacuum and ε_r – relative permittivity of sample (without or with trees).

2.1. Needle-plane samples

The geometrical model related to the needle-plane sample (Fig. 1) having water trees under the shape of a sphere with a known rayon R is presented in Figure 5. The needle electrode has a conical shape, rounding radius being r_0 and the distance between the two electrodes – d (Notingher et all, 2000).

Variation of the electric field strength E – for a needle electrode with the radius r_0 = 10 μm at the distance d = 2.5 mm from plane electrode and a tree with the radius R = 100 μm, for $U = V_1 - V_2 = 5$ kV – with y coordinate is presented in Figure 6. It can be seen that, in the presence of the tree, the electric field strength decreases in the needle vicinity, but increases in the area between the tree front and the plane electrode. In the case of the needle-needle samples (being at the same distance d each other) E takes higher values also in the vicinity of the second electrode (Radu, 1997).

2.2. Plane samples

The geometrical model related to polyethylene flat samples (Fig. 2) of thickness g, containing individual trees with a known length a is presented in Figure 7 (Radu et all, 2000). Trees are considered having the shape of semi-ellipsoids with the major axis $2a$ and the minor axis $2b$.

Variation along the axis Oy of the electric field strength in the absence and presence of trees with different lengths is presented in Figure 8. It can be seen that, with the increase of trees length, the electric field strength increases. Thus, in the case of a tree with a known length 0.48 mm, the electric field strength increases with almost 50 %.

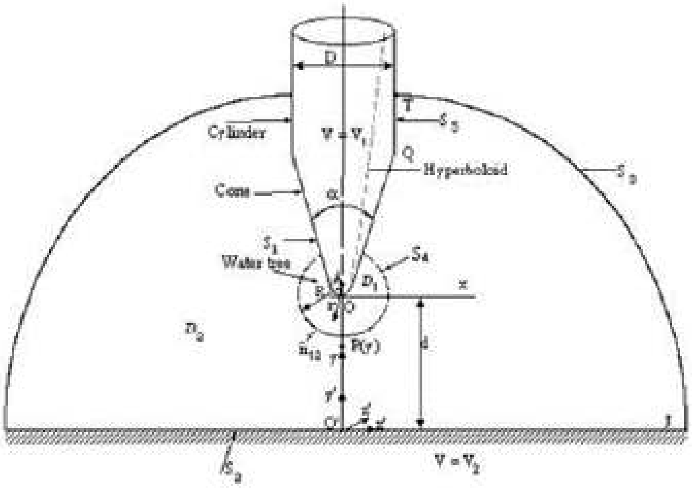


Fig. 5. Needle-plane samples domain for electric field computation.

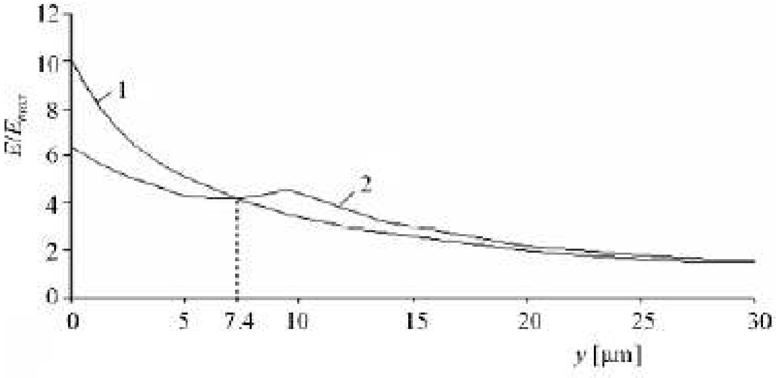


Fig. 6. Variation of the ratio E/E_{max} along the y - axis ($x = 0$), for $r_0 = 10$ μm, $d = 2.5$ mm and $U = 5$ kV, in the absence of water trees (curve 1) and in the presence of a tree with $R = 10$ μm (curve 2).

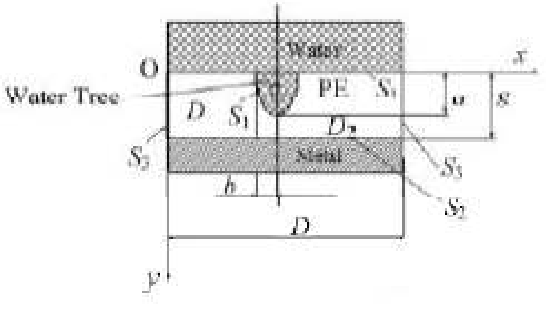


Fig. 7. Plane samples domain for electric field computation.

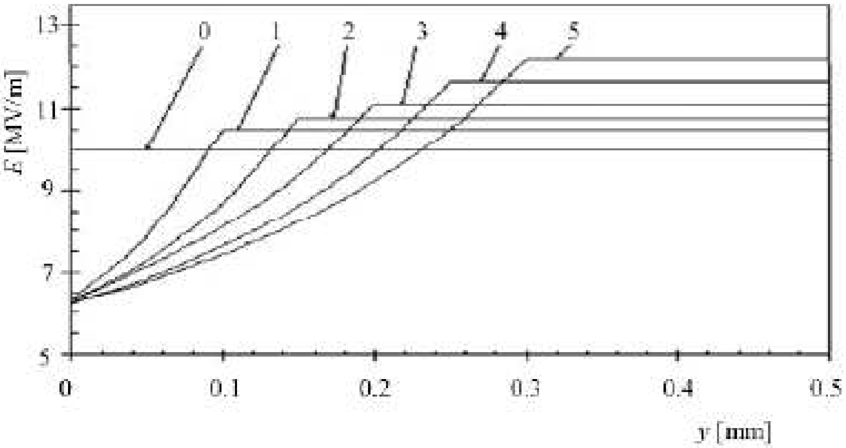


Fig. 8. Electric field distribution as a function of co-ordinate y for different water tree lengths in a plane sample: (0) $a = 0$; (1) $a = 0.1$ mm, (2) $a = 0.15$ mm, (3) $a = 0.2$ mm, (4) $a = 0.25$ mm, (5) $a = 0.3$ mm.

2.3. Cylindrical samples

The geometrical model related to cylindrical samples, respectively medium voltage cables polyethylene insulated (of outer r_2 and inner r_1 radius) presenting trees developed from both semiconductor layers (outer - W_{T1} and inner - W_{T2}) and with ionic space charge layers of density ρ_{vmed} is presented in Figure 9 (Stancu et all, 2009).

In Figure 10 variation of the electric field strength with the coordinate r in the case of trees and space charge layers with the same length $l_{a1} = l_{a2} = l_{s1} = l_{s2} = 0.5$ mm and 20 kV applied voltage is presented. It can be seen that in the trees vicinity important increases of the electric field appear.

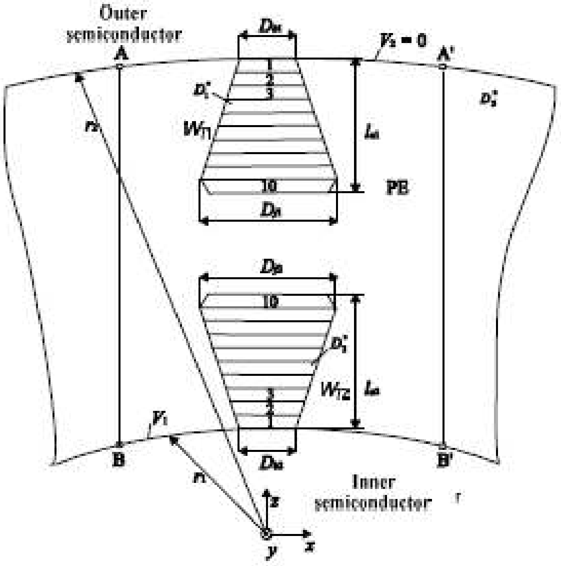


Fig. 9. Computation domain for two individual water trees (W_{T1} and W_{T2}).

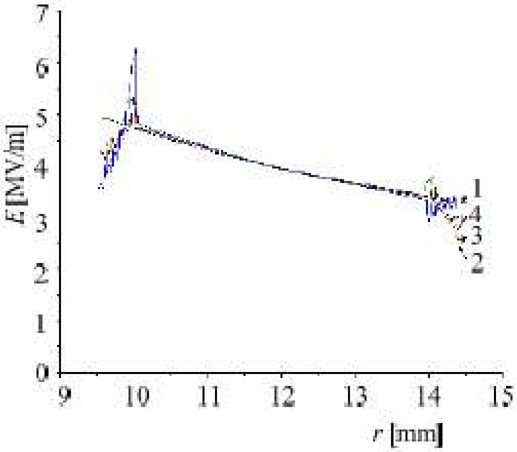


Fig. 10. Variation of E with r in the absence of trees and charge (1) and in the presence of 2 individual trees of $l_{a1} = l_{a2} = 0.5$ mm (2), two charge layers of $l_{s1} = l_{s2} = 0.5$ mm and $\rho_{vmed} = 0.106$ C/m^3 (3) and two individual water trees and two charge layers of $l_{a1} = l_{a2} = 0.5$ mm, $l_{s1} = l_{s2} = 0.5$ mm and $\rho_{vmed} = 0.106$ C/m^3 (3) ($V_1 = 20$ kV).

2.4. Electric field effect

Analyzing the curves presented in Figures 6, 8 and 10 it can be observed that the water trees and ionic space charge existence determines a modification of the electric field repartition, respectively an intensification of the electric field in treed areas. This increase determines modifications of partial discharges V_{apd} and electrical trees V_{aet} inception voltages in these samples (Radu, 1997).

Variations of the quantities V_{apd} and V_{aet} are presented in Figures 11 and 12. It can be seen that the increase of water trees length determines an important decrease of V_{apd} and V_{aet}. As a consequence the breakdown voltage values decrease also.

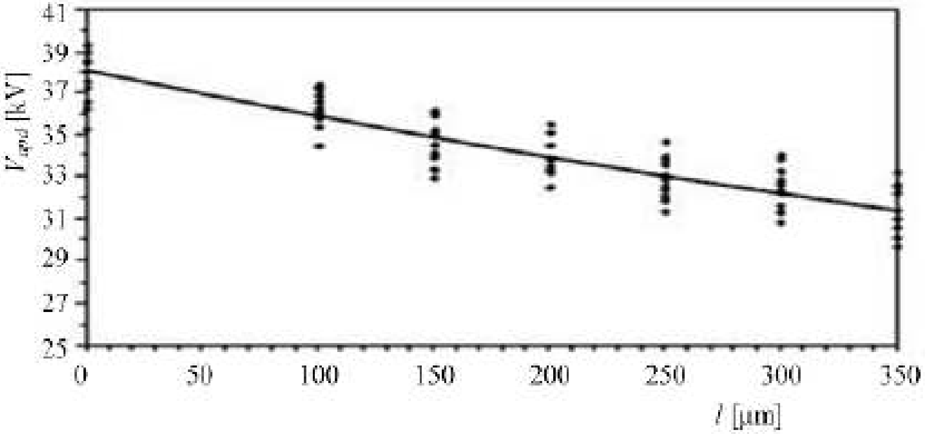


Fig. 11. Variation of partial discharges inception voltage V_{apd} with water trees length l (needle-needle samples).

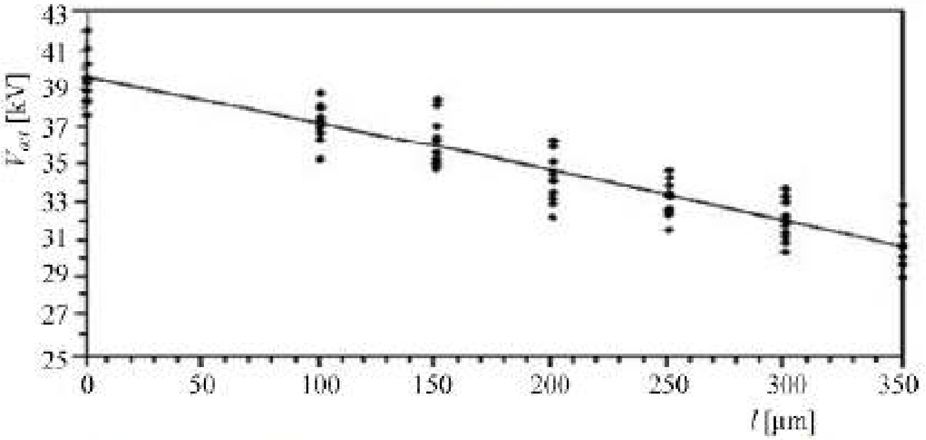


Fig. 12. Variation of electrical trees inception voltage V_{aet} with water trees length l (needle-needle samples).

3. EXPERIMENTS

In order to verify the results obtained by computation, regarding the decrease of breakdown voltage due to water trees development, experiments on needle-plane and model cables samples, respectively on polyethylene insulated conductors, were done.

3.1. Samples

Technologies used to manufacture the needle-plane and needle-needle samples but also the setup used to measure the partial discharge and electrical trees inception voltage are presented in several papers (Filippini et all, 1988, Filippini et all, 1988, Radu, 1997)

Cylindrical samples (model cables) used in this study are taken from a single-wire copper conductor (with a diameter of 1.1 mm) insulated with low density polyethylene of thickness 0.8 mm), manufactured at IPROEB Bistrita. The samples length was 50 mm.

In order to reduce the inception and development time of water trees, on the outer surfaces of the model cables superficial defects were done. For a better control of the defects, the samples were covered with abrasive paper type P240 and placed between two plates provided with cylindrical groves having a superior diameter than those of samples. The samples were then pressed at a pressure $p = 2\ldots20$ MPa by using a CARVER hydraulic compression head.

On a 10 samples group the breakdown voltage was measured by using an automatic setup which allows the control and adjustment of the voltage growth rate between 0.06 and 2.4 kV/s.

Setup used to develop water trees in an accelerated manner is presented (Stancu, 2010). Water trees dimensions were measured by using the setup presented in Figure 13.

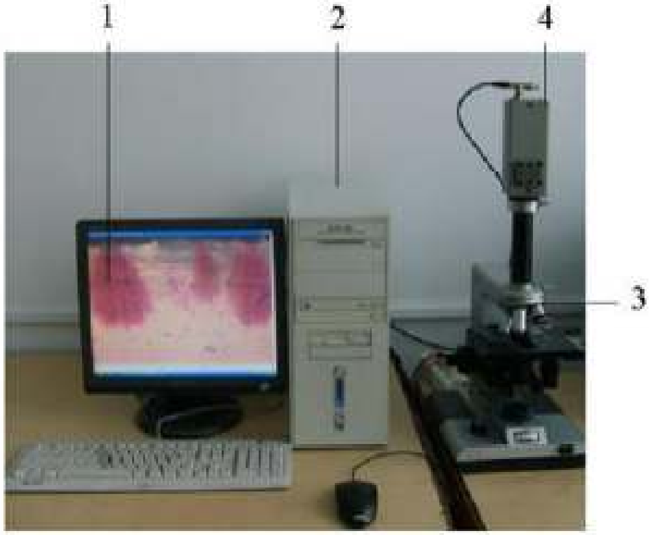


Fig. 13. Setup used for measuring the dimensions of the water trees: (1) – Vented tree, (2) – PC, (3) – Microscope, (4) – Camera.

3.2. Breakdown voltage measurement

In order to measure the breakdown voltage a PMMA paralelipipedic special cell was built up. The samples insulation was covered with a copper band having 100 mm and the un-insulated ends were introduced in two metallic balls to avoid electrical discharges. The voltage growth rate was 1 kV/s, so that the time until breakdown of insulation should be according to the SFS 5791/1994-10-10 12/20 kV PAS p. 6.1.4.

After the breakdown measurements the average value $V_{b,a}$:

$$V_{b,a} = \frac{\sum_{i=1}^{n} V_{b,i}}{n} \qquad (3)$$

and the standard deviation σ

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} \left(V_{b,i} - V_{b,a}\right)^2}{n}} , \qquad (4)$$

where $V_{b,i}$ represents the breakdown voltage of the sample, i and n – the number of samples remained after the wrong values elimination, were computed.

3.3. Water trees development

The methods used to develop water trees in needle-plane and needle-needle samples were presented (Notingher et all, 2005, Filippini et all, 1988, Radu, 1997).

In the cylindrical samples case, these were introduced on a 300 mm length in a PMMA cell filled with a NaCl solution of 0.1 mole/l concentration. Un-insulated ends of the samples were connected to the high voltage terminal of a transformer. The RMS value of the voltage was 5 kV, which ensure a strength of the electric field on the outer surface of the samples of 4 kV/mm. The ageing time varies between 25 and 264 h.

3.4. Dimensions and density of water trees

After the voltage is switched off, from their active area 3-5 slices were taken and introduced in a rhodamine solution at T = 60 °C for 72 h. Then, from each area slices of thickness of 200 µm were taken and the dimensions of the trees were measured.

Water trees were considered under the cylindrical shape (of length L and diameter D). The average length L_a and diameter D_a were computed by using the relations:

$$L_a = \frac{1}{N_w} \sum_{k=1}^{N_w} L_k \qquad (5)$$

$$D_a = \frac{1}{N_w} \sum_{k=1}^{N_w} D_k , \qquad (6)$$

where N_w represents the total number of trees on 5 slices, L_k – the length and D_k - the diameter of the tree *k* (Fig. 14).

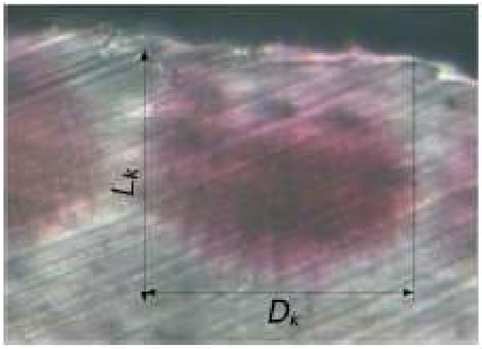


Fig. 14. Measurement of the length L_k and diameter D_k of the tree.

4. RESULTS

4.1. Water trees

The water trees dimensions and densities in cylindrical samples (model cables) in different development steps, respectively for different ageing times are presented in Table 1. It can be observed that the dimensions and densities of the trees increase with the ageing time. These modifications determine local increases of the electric field and in consequence a decrease of the partial discharge and water trees inception voltage (see par. 2).

Table 1. Values of the average breakdown voltage $V_{b,a}$
and average dimensions of water trees developed in model cables.

Ageing time [h]	0	25	96	165	264
Breakdown voltage [kV]	38	25	23	12.2	10.3
Average length [μm]	-	112	197	300	609
Average diameter [μm]	-	101	152	240	359
Trees density [mm^{-2}]	-	1	2	4.5	6

4.2. Breakdown voltage

In the needle-needle samples case (d = 1 mm) variation of the average breakdown voltage with tree length is presented in Figure 15. Measurements were done on groups of 10 samples. It can be seen that the breakdown voltage values decrease with the increase of trees length, due to the increase of the electric field outside the treed areas and the decrease of the partial discharge level (Fig. 11) as well as electrical trees inception voltage (Fig. 12) (Heinhold, 1993).

Noted that breakdown channels avoid the treed areas (Fig. 16) because in these areas (with higher permittivity than other areas) on one hand the electric field is much lower and on the other hand water slows the partial discharges and electrical trees inception.

Results obtained on cylindrical samples are presented in Table 1. It can be seen that, a significant decrease of the breakdown voltage with the increase of the ageing time appears also. This is due to the increase of dimensions and densities of the trees with the increase of τ, respectively a local intensification of the electric field, according with the theoretical results presented in par. 2.

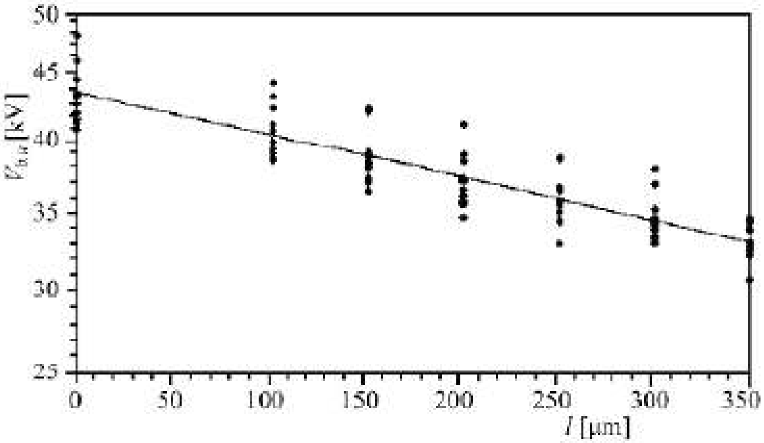


Fig. 15. Variation of average breakdown voltage $V_{b,a}$ function of trees length l in needle-needle samples (d = 1 mm).

5. CONCLUSIONS

The electric field amplification at the front and ahead of the water trees can reach dangerous values for the insulation, if natural or created defects are present in the polymer facing the water tree zone.

The local field amplification mechanism based on the dielectric nature of the treed degraded zone appears as a plausible explanation of the water treeing induced breakdown. It is in agreement with the random nature of the phenomenon, related to the probability of presence of defects and confirms the extremely important role played by those defects which may be acceptable in the absence of water trees but which can become breakdown initiation points, and then a serious handicap for electric service performance, if water trees are present in their vicinity.

Fig. 16. Breakdown of a low density polyethylene needle-needle sample with trees.

ACKNOWLEDGEMENTS

The authors are gratefully to Romanian Ministry of Education, Research, Youth and Sport for the financial support under the projects DEDIC no. 34/2010 and CABDIAG no. 22122/2008.

REFERENCES

1. Steennis, E.F., Kreuger, F.H. (1990) Water Treeing in Polyethylene Cables, IEEE Trans. Electr.Ins., 35 (5), pp. 989-1028.
2. Ross, R., Effect of ageing conditions on the type of water treeing, IEEE Transactions on Electrical Insulation Magazine, 9, 1993, pp. 7 – 13.
3. Notingher, P.V. (2005) Materials for electrotechnics, 1, Bucharest, POLITEHNICA Press.
4. Notingher, P.V. (2005) Water Treeing Method for Insulation Ageing State Characterization, Proceedings of The First Workshop of Electrical Engineering Materials and Applications, Bucharest, pp. 117-125.

5. Dissado, L.A., Wolfe, S.V., Filippini, J.C., Meyer, C.T., Forthergill, J.C. (1998) An Analysis of Field – Dependent Water Tree Growth Models, IEEE, Trans. on Electrical Insulation, 23 (3), pp. 345 – 356.

6. Filippini, J.C., Meyer, C.T. (1988) Water treeing test using the water needle method: the influence of the magnitude of the electric field at the needle tip, IEEE Trans. Electrical Insulation, E.I. 23 (2), pp. 275 – 278.

7. Notingher, P.V., Ciuprina, F., Radu, I., Filippini, J.C., Gosse, B., Jipa, S., Setnescu, T., Setnescu, R., Mihalcea, T. (1996) Studies on treeing and chemiluminescence on irradiated polyethylene", IEEE International Symposium on Electrical Insulation, June 16 – 19 Montreal, pp. 163 – 166.

8. Notingher, P.V., Ciuprina, F., Radu, I. (1998) The Influence of Ageing Process on the Shape and the Propagation Kinetics of the Water-Trees in Needle-Plane Polyethylene Samples, Proceedings of 6th International Conference on Conduction and Breakdown in Solid Dielectrics, Vasteras, pp. 341-344.

9. Dissado, L., Fothergill, J.C. (1992) Electrical Degradation and Bbreakdown in Polymers, Peter Pelegrinus Ltd., London.

10. Ciuprina, F., Teissèdre, G., Filippini, J. C., Notingher, P. V., Campus, A., Zaharescu, T. (2004) Water treeing in chemically crosslinked polyethylene, Journal of Optoelectronics and Advanced Materials, 6 (3), pp.1077-1079.

11. Filippini, J.C., Meyer, C.T. (1988) Water treeing test using the water needle method: the influence of the magnitude of the electric field at the needle tip, IEEE Trans. Electrical Insulation, E.I. 23 (2) pp. 275 – 278.

12. Radu, I. (1997) Comportarea unor materiale electroizolante in campuri electrice intense, PhD Thesis, UPB.

13. Stancu, C. (2008) Caractérisation de l'état de vieillissement des isolations polymères par la mesure d'arborescences et de charges d'espace, PhD Thesis.

14. Notingher, P. V., Stancu, Cristina, Plopeanu, M., Grigorescu, S. (2010) The influence of water trees on permittivity and loss factor of medium voltage cables polyethylene insulation, Proceedings of the IEEE International Conference on Solid Dielectrics (ICSD), Potsdam, Germany, pp. 671 – 674.

15. Ciuprina, F., Notingher, P.V. (2003) Estimation of the Conductivity of Water-treed Regions in Polyethylene, Actes du colloque "Materiaux du Genie Electrique", Grenoble, pp.78-80.

16. Stancu, Cristina, Notingher, P. V., Platbrood, G., Notingher, P. P. (2008) Influence of the Surface Defects on Water Trees Development, Proc. of International Conference Materials for Electrical Engineering (MmdE), Bucharest, Romania, pp. 413-418.

17. Notingher, P. V., Stancu, Cristina, Plopeanu, M., Lingvay, I. (2010) Dielectric properties of polyethylene subjected to electric field in the presence of water, 12th International Symposium MATERIALS, METHODS & TECHNOLOGIES (MM&T), Sunny Beach, Bulgaria, Journal of International Scientific Publications: Materials, Methods & Technologies, 4, Part 2, pp. 91 – 104.

18. Nakamura, S., Kawai, J. (2001) Relative Permittivity and Conductivity of Water – Treed Region in Cross-linked Polyethylene, IEEE 7th International Conference on Solid Dielectrics, pp. 163 – 166.

19. Hai, V.T. (2006) Final Breakdown on Water Tree Degraded Polymer Insulation, Advances in

Natural Sciences, 7 (1&2), pp. 57-61.

20. Radu, I., Acedo, M., Notingher, P.V., Frutos, F., Filippini, J.C. (1996) A study of the Dependence of Water-tree Permittivity with Time, Annual Report of Conference " Electrical Insulation and Dielectric Phenomena", San Francisco (USA), 2, pp. 762-765.
21. Notingher, P. V., Radu, I., Filippini, J.C. (1995) Electrical field calculations in polymers in presence of water trees, Proceedings IEEE 5th International Conference on Conduction and Breakdown in Solid Dielectrics, IEEE Publication, Leicester, pp. 666 – 670.
22. Notingher, P.V., Radu, I., Filippini, J.C. (2000) Numerical Method of Computation of the Electric Field in Insulation with Water-Trees. Part I: Computation Methods, Rev.Roum.Sci.Tech-Electr. et Energ., 45 (2), pp. 221-236.
23. Notingher, P.V., Radu, I., Filippini, J.C. (2000) Numerical Method of Computation of the Electric Field in Insulation with Water-Trees. Part II: Influence of Water Trees, Rev.Roum.Sci.Tech-Electr. et Energ., 45 (4), pp. 563-574.
24. Radu, I., Acedo, M., Notingher, P.V., Frutos, F., Filippini, J.C. (1997) The Danger of Water-Trees in Polymer Insulated Power Cables Evaluated from Calculations of Electric Field in the Presence of Water Trees of Different Shapes and Permittivity Distributions, Journal of Electrostatics, 40-41, pp. 343-347.
25. Radu, I., Notingher, P.V., Filippini, J.C. (2000) Influence of Water Trees on the Electric Field Distribution and Breakdown in the Point-Point Geometry, Journal of Electrostatics, Fundamentals, Applications and Hazards, (48), pp.165 – 178.
26. Radu, I., Acedo, M., Filippini, J.C., Notingher, P.V. and Frutos, F. (2000) The Effect of Water Treeing on the Electric Field Distribution of XLPE: Consequences on the Dielectric Strength, IEEE Transactions on Dielectrics and Electrical Insulation, 7 (6), pp.860-868.
27. Acedo, M., Radu, I., Frutos, F., Filippini, J.C. and Notingher, P.V. (2001) Water Treeing in Underground Power Cables: Modelling of the Trees and Calculation of the Electric Field Perturbation, Journal of Electrostatics, 53, pp. 267-294.
28. Stancu, C., Notingher, P.V., Ciuprina, F., Notingher, P. jr, Agnel, S., Castellon, J., Toureille, A. (2009) Computation of the Electric Field in Cable Insulation in the Presence of Water Trees and Space Charge, IEEE Transactions on Industry Applications, 45 (1), pp. 30-49.
29. Stancu, Cristina, Notingher, P. V., Notingher, P. jr, Plopeanu, M. (2009) Electric Field Determination in Water Treed Samples Using the Thermal Step Method, 11th International Symposium MATERIALS, METHODS & TECHNOLOGIES (MM&T), 3 - 7 June 2009, Sunny Beach, Bulgaria, Journal of International Scientific Publications, Materials, Methods & Technologies, 3, Part 1, pp. 51-62.
30. Visata, O.I., Teissedre, G., Filipinni, J.C., Notingher, P.V. (2001) An Investigation on the Distribution of Ions and Water in Water Trees by FTIR Microspectroscopy, In: Proceedings of the "7th International Conference on Solid Dielectrics – ICSD'01, Eindhoven, June 25-29.
31. Stancu, Cristina, Notingher, P.V., Stoica, C., Plopeanu, M., Notingher, P. jr. (2010) Influence of Dimensions and Density of Water Trees on Residual Electric Field in Polymeric Power Cables Insulations, Revue Roum. Sci. Tech. - Electr. Et Energ., Tome 55 (3), pp. 289-299.
32. Heinhold, L., Stubbe, R. (1993) Power Cables and their Applications, 3rd Edition, Siemens Aktiengesselschaft, Berlin.
33. Stancu, C. (2010) Electrical degradation and lifetime reserve estimation of polymeric cables insulations, Project PD-RU-34/2010.