Journal of Electrostatics 71 (2013) 145–154

Contents lists available at SciVerse ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Influence of space charge related to water trees on the breakdown voltage of power cable insulation

Cristina Stancu [a,*], Petru V. Notingher [b], Petru Notingher Jr. [c]

[a] National Institute for R&D in Electrical Engineering, 313 Splaiul Unirii Street, Bucharest 030138, Romania
[b] University POLITEHNICA of Bucharest, Romania
[c] Université MONTPELLIER 2, France

A R T I C L E I N F O

Article history:
Received 10 April 2012
Received in revised form
12 September 2012
Accepted 24 December 2012
Available online 22 January 2013

Keywords:
Cables
Water trees
Space charge
Electric field
Failure

A B S T R A C T

A three-dimensional computation of the electric field and breakdown voltage in power cable insulation containing water trees and space charges is presented. The breakdown voltage and the conductivity of cylindrical samples of cable insulation containing water trees were measured. The samples have been aged in wet environment under ac voltages of frequencies comprised between 1 and 5 kHz. Exponential and parabolic spatial variations of permittivity and space charge density and the electrostatic, electrokinetic and quasi-stationary regimes of the electric field were considered. The best correlation between the experimental breakdown voltage and the calculated one has been obtained in quasi-stationary regime.

1. Introduction

Water trees, which are diffuse areas of insulations constituted of water-filled cavities connected by thin channels (Fig. 1), represent a major cause of premature breakdown of polymer-insulated cables during service [1–3]. The inception and development of water trees are essentially due to the appearance of high electric fields either at interfaces (leading to the growth of vented trees, Fig. 1) or in the insulation bulk (where bow tie trees develop).

The main consequence of water treeing is the modification of the electric field repartition (the field increases in the neighbouring areas of the trees [4–8]) and the decrease of the electrical properties of the dielectric [9]. Indeed, calculations done on polyethylene insulations of medium voltage cables have shown a 30% increase of the electric field near the water trees fronts [10].

On the other hand, water trees development leads to the appearance of ionic space charge (Na^{+}, Cl^{-} etc.) both inside the trees and in their neighbourhood [10,11]. Space charge generates a supplementary local enhancement of the electric field leading to an increase of more than 50% with respect to the case where the insulation does not contain water trees and space charge [12]. Thus, the value of the voltage may exceed locally the critical values for the inception of partial discharge (8.5–11 kV for polyethylene [13]) or electrical trees (8 kV for polyethylene [14]). Indeed, partial discharges and electrical trees are initiated in the presence of water trees at lower values of the applied voltage [13,14].

An experimental study performed on model cables on the issue of the dependence of the breakdown voltage on the water tree dimensions [15] concluded that the breakdown voltage does not depend on the tree density, but it diminishes when the length of the water trees increases [15].

Computations of electric field in insulations with water trees or space charge are presented in different papers. Thus, different models and procedures for the calculation of the space charge and electric field distribution in dc cables, in electrostatic and electro kinetic stationary regime, but in the absence of water trees, are presented in Ref. [16]. In Refs. [10,12,17], electric field computations in electrostatic regime considering insulations with continuous or individual trees, in the presence [10,12] or absence of space charge [17] are presented.

In most of the cases reported in the literature, the electric field computation is done in electrostatic regime (i.e. [4–8,12,16]) and the breakdown voltage is determined experimentally in variable regime (quasi-stationary or harmonic). Considering that the reduction of the breakdown voltage with time is due to the water trees growth and to the increase of the amount of space charge related to water trees, the present paper deals with computing the

* Corresponding author. Tel.: +40 213467235; fax: +40 213468299.
E-mail address: cstancu@icpe-ca.ro (C. Stancu).

0304-3886/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.elstat.2012.12.041

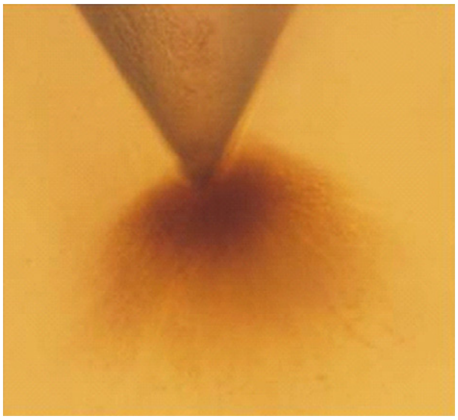

Fig. 1. Vented tree developed in low-density polyethylene.

values of the electric field in polyethylene insulation. The work is made using model cables with individual water trees of variable lengths and space charge layers of variable thickness and densities. The computations are made in electrostatic, electro kinetic and quasi-stationary regimes.

First, the breakdown voltages of polyethylene-insulated model cables without water trees have been measured experimentally, and the maximum values of the electric fields corresponding to the measured breakdown voltages were calculated. These experimentally-determined breakdown fields in samples without water trees are noted E_{br}. Assuming that in the presence of water trees and space charge breakdown occurs for values of the applied voltage for which the maximum values of the field (noted E_{max}) are equal to E_{br}, the characteristics of ionic charge layers associated to water trees have then been determined after breakdown experiments carried out on water-treed samples. Thus, we have computed the thickness of the space charge layers l_s and the average value of charge density ρ_{va} for which the applied voltage is equal to the breakdown voltage in the treed insulations. Different regimes of the electric field have been considered. As it will be shown herein after, the results show that, whatever the trees length, the values of the space charge layer length and density for which the maximum field in the insulation approaches the breakdown field are obtained in the case of the electro kinetic quasi-stationary regime of the electric field.

2. Experiments

2.1. Samples

Samples taken from low-density polyethylene insulated model cables have been used. The characteristics of the insulation were the following: thickness: 0.8 mm, inner radius (respectively the conductor radius) $r_i = 0.55$ mm, outer radius $r_e = 1.35$ mm, length: 50 cm. The samples have been thermally conditioned at a temperature $T = 60$ °C during 72 h.

2.2. Water trees development

Water trees were developed on groups of 6 samples, which have been aged under a RMS voltage $V_a = 5$ kV of frequencies between 50 and 3 kHz for times between 24 and 1320 h. Before applying the voltage, superficial defects have been created on the surface of each sample in order to reduce the inception times of water trees (and thus the duration of the tests). Each defect has been produced on a distance of 30 cm on the sample surface. The defects were produced by pressing at 1 tf. Then, groups of 2 samples have been introduced in a cell filled with a H_2O/NaCl solution of concentration equal to 0.1 mol/l (Fig. 2).

In order to reduce the electrical stress on the insulating areas in contact with the air (especially at the air–electrolyte interface), each insulation has been thickened by covering with 3 polyethylene shrink tubes. The samples have been connected to a transformer (“T”, Fig. 2), and the test voltage V_a was applied. After the voltage has been switched off, 5 slices of average thickness of 0.2 mm were taken from each sample in order to measure the dimensions of the grown trees (Fig. 3). For each group of samples, the lengths and the diameters of the water trees were measured on 30 slices.

2.3. Measurement of the breakdown voltage

The breakdown voltage was measured on groups of 6 samples by using an automatic facility, which allows the adjustment of the test parameters (voltage ramp, time-to-breakdown etc.) [18]. The voltage ramp was 1 kV/s, according to ASTM D149-09. Each result was recorded by a computer for processing.

3. Computation of the electric field

The assumed computation domain is presented in Fig. 4. It represents a section of the insulation of a sample (model cable) of length $l = 5$ mm, inner surface (S_1) of radius r_i and outer surface (S_2) of radius r_e and lateral surfaces S_{l1} and S_{l2}. The latter are circular crown defined by the radii r_i and r_e. It is considered that the insulation presents an individual water tree of semi-spherical shape of surface S_{23}, centre O′ and radius equal to the maximum length l_{wt} of the trees measured on the sample on which the section was cut. A space charge layer of average density ρ_{va}, also of semi-spherical shape (of surface S_{12}, centre O′ and radius l_s) is assumed both inside and outside the trees (Fig. 4). Thus, the computation domain $D = D_1 \cup D_2 \cup D_3$ includes:

- the subdomain D_1, defined by the surfaces S_1, S_2, S_{23}, S_{l1} and S_{l2}, corresponding to the area without water trees and without space charge;
- the subdomain D_2, defined by the surfaces S_2, S_{12} and S_{23}, corresponding to the area without water trees, but containing space charge;
- the subdomain D_3, defined by the surfaces S_2 and S_{12}, corresponding to the area containing water trees and space charge.

3.1. Equations

The equations used to compute the electric field E were chosen according to the electric field regime: electrostatic, stationary electro kinetic and quasi-stationary.

3.1.1. Electrostatic regime

a) The electric displacement law

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

b) The connection law between the electric displacement $\overline{D}$ and the electric field $\overline{E}$

$$\overline{D} = \varepsilon\overline{E}; \tag{2}$$

c) The theorem of electrostatic potential