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The method of testing of XLPE cable insulation resistance to partial discharges and electrical treeing

M JEVTIC* and A M ANDREEV†
University of Belgrade, Technical faculty in Bor, 19210 Bor, Yugoslavia
†Saint-Petersburg Technical University, Electro-mechanical faculty, Saint-Petersburg, Russia

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Abstract. The paper gives a method of model XLPE medium voltage cable insulation testing for partial discharges and electrical treeing with a point to plane test geometry. Based on this method, a comparative estimate of insulation resistance to treeing and partial discharges have been made. XLPE crosslinked by different methods (steam medium and hot nitrogen medium) and with varying contents of inorganic filler kaolin were tested. The characteristics of partial discharges were measured by means of a pulse height analyser characterized with a microscope. The data have been analysed statistically.

Keywords. Electrical treeing; partial discharges; XLPE cable insulation.

1. Introduction

Medium voltage cables using crosslinked polyethylene (XLPE) dielectric are manufactured by various methods of crosslinking and with various additives and fillers, to achieve most optimal operational characteristics. Electrical trees (Tanaka 1986), water trees (Steennis and Kreuger 1990), electrochemical trees (a small subclass of water trees) (Ku and Liepins 1987) and chemical (sulphide) trees (Gherardi and Metra 1983) cause long-term electrical failures in polymer cable dielectrics. The failure statistics reflect the relative resistance of different materials and cable constructions to treeing.

The purpose of this work was to develop a method of assessing the insulations based on their resistance to partial discharges and electrical treeing. Models of XLPE medium voltage cable insulation were constructed for this purpose, which are as close to the actual cables as practicable.

2. Experimental

Three types of cable dielectrics were tested: (i) XLPE with kaolin as filler, steam-crosslinked (type ELKEN 2003–10, ELKA Zagreb, experimental qty); (ii) steam crosslinked XLPE without filler (type HFDM 4201 BP) and (iii) XLPE crosslinked under hot nitrogen without filler (HFDM 4201 BP).

Dielectric (i) consisted of low density XLPE, inorganic filler kaolin, additives (antioxidant, peroxide) in the mass proportion of 100:20:5. Immediately after manufacture of cables, the insulation with filler had high loss tangent (tg δ) value ($6{\cdot}5 \times 10^{-3}$) compared to the other cable specimens (table 1). After thermal treatment (90°C/60 h) of the cable sample, low molecular additives were separated from the dielectric and value of tg δ came down to 25×10^{-4}. The same reduction of value of tg δ was observed on cable samples stored at room temperature for the period of 1 year. Also, the other electrical properties of cable without filler were, in general, somewhat better than those

Table 1. Electrical properties of tested insulations.

Property	Cable specimen I	II	III
Dielectric constant (50 Hz, 20°C)	2·38	2·30	2·30
tg $\delta \times 10^{-4}$ (50 Hz, 20°C)	25·10	6·30	5·10
Electric resistivity $\times 10^{15}$ (20°C), Ω m	0·82	2·20	3·20
Electric breakdown stress 63·2% Weibull probability, kV/mm*	55·20	70·50	—
Electric breakdown stress 63·2% Weibull probability after ageing in NaCl solution, kV/mm**	43·90	32·90	—
Factor n of life curve $t = k \times U^{-n}$	15 ± 3	12 ± 2	—

* Electric breakdown stress was determined on model of a medium voltage cable with a dielectric thickness of 0·9 mm. The effective length of specimen was 1·5 m, rate of increase of voltage was 1 kV/s.
** Electric breakdown stresses were measured after immersing the specimens in 0·01 N NaCl solution with simultaneous exposing to voltage (13 kV, 50 Hz) and thermal cycles (16 h/65°C and 8 h/20°C) over a period of 1000 h.

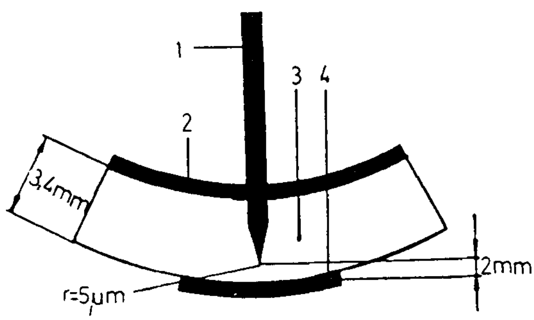

Figure 1. Test specimen (XLPE cable insulation cut). 1. High voltage tungsten needle electrode, 2. first semiconductive layer, 3. insulation and 4. second semiconductive layer (grounded electrode).

for cable with filler (table 1) due to the presence of the filler. However, the filler was used in crosslinking polyethylene (ELKEN 2003-10) to reduce their cost and to improve mechanical properties of the cable dielectric on operational temperature (Shintic 1986).

The processes of growth of electrical trees were investigated at samples consisting of insulation cuts from manufactured cables (figure 1). Electrical treeing of ac excitation was due to the internal partial discharge within the polymer under a high electrical field. Electrical trees grow by partial discharge, causing decomposition of material, and produce small hollow channels (Tanaka 1986). The energy sources of chemical decomposition come from the discharge energy of the gas (bombardment of accelerated charged particles, and thermal conduction) and the static energy of the field. The whole process of electrical treeing can be divided into two distinct stages: (i) the inception stage and (ii) propagation stage. The relative duration of each stage is different for different cases, and the shape of the tree formed in each case is determined by the relative time difference (Ku and Liepins 1987).

The tests were done in accordance with the known methods (Mc Mahon 1978) when trees in the specimens were formed at the tip of the needle high voltage electrode. The specimens (figure 1) were prepared for testing in the following way: a tungsten needle with radius of the needle tip $r = 5 \pm 0{\cdot}5$ μm was inserted in the cut of cable dielectric of 3·4 mm thickness on a fixed depth. The distance of a needle tip to the second semiconductive layer was 2 mm. Before testing, needles were sharpened by a method of electrolysis in 10% KOH solution and the tips were measured by means of an electronic microscope. All prepared specimens were observed by means of a microscope in order to eliminate test specimens with voids or impurities near the tips. After that, the specimens were put in a special cell and immersed in degassed silicon oil. Ten specimens were simultaneously tested in the cell and partial discharges were measured in each specimen. The needle represented high voltage electrode and second semiconductive layer was grounded electrode. As a criterion of electrical treeing resistance the following items were used: partial discharge inception voltage U_i, maximum lengths of electrical trees l, developed characteristics of partial discharge during growth of trees (maximum apparent charges Q_m and frequency of partial discharge N). The characteristics of partial discharge were measured by means of multichannel pulse height analyser, with a detection level of 10^{-13} C. The tests were performed with alternating voltage at 50 Hz and at room temperature.

The average value of experimentally obtained voltages at which stable partial discharge appear (frequency $N \geqslant 10\,\mathrm{s}^{-1}$, $Q_m \geqslant 10^{-12}$ C) in the specimens was taken as the U_i. Determination of U_i value was done by the method of step by step increase of test voltage. The magnitude of a step was 1 kV, step duration time was 1 min. The U_i value was calculated:

$$U_i = (U_n + U_{n-1})/2, \tag{1}$$

where U_n is voltage value on n-step on which measured partial discharges with $Q_m \geqslant 10^{-12}$ C and $N \geqslant 10\,\mathrm{s}^{-1}$ occurred. On the basis of experimentally determined U_i value, the constant value of test voltage and time intervals for Q_m, N and l measurements were chosen.

3. Results and discussion

On the basis of the partial discharge measurement, it was established that the filled cable (I) had lower values of U_i than unfilled cables (II and III) in the proportion of 2·5 : 6·5 : 12·5 (kV). However, the intensity of partial discharge at U_i for the filled XLPE was considerably lower (frequency of partial discharges was 10...15 s^{-1} vs 400...500 s^{-1} for cable II and 100...200 s^{-1} for cable III). It was obvious that the lower value of U_i for specimens of filled XLPE was due to their inhomogeneous structure, and hence partial discharges appeared in microvoids, and homogeneous unfilled cables showed a tendency of increased discharge activity (soon after inception) in the highly stressed volume around the needle tip.

Microscopic observations of dielectric thin plates around the needle tip showed that on specimens of unfilled XLPE the value of U_i correspond to the inception of tree and in the case of filled XLPE, the trees were not initiated at U_i but a higher test voltage was required for initiation. It is obvious that particles of kaolin create dielectric barriers decelerating the growth of trees. This is confirmed by results obtained after 3 h of

Table 2. Probability of electrical trees occurrence after 3 h of exposure of the test specimens to the test voltage of 6 kV.

Insulation sample	I	II	III
Number of specimens wherein trees were created (%)	31	100	75
Number of specimens wherein breakdown between electrodes occurred (%)	0	25	0

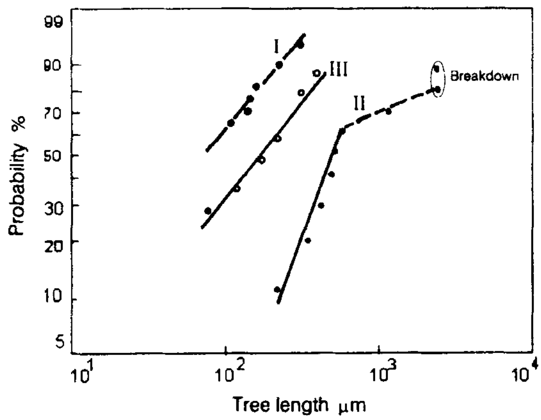

Figure 2. Distribution of electrical trees lengths in the specimens of cables I, II and III.

exposure of the test specimens to the test voltage of 6 kV (table 2). The lengths of trees and their shapes were measured and determined on plates of about 200 μm thickness by a microscope. The lowest probability of electrical trees occurrence was established for specimen I (table 2). The presence of kaolin enables increased resistance of filled XLPE to initiation and propagation of trees compared to other specimens. The lengths of trees in specimen I were approximately half as that of specimen III and almost ten times shorter than for cable II (figure 2).

Microscopic observations showed that electrical trees in specimen III had branch-shape and in specimens I and II bush-shape. Such tree shapes are probably due to the diffusion rate of gaseous products of polyethylene decomposition in tree channels. If gases separate intensively, and the diffusion rate is low, discharges will be temporarily smothered due to gas pressure so that the channels of trees will be shorter and numerous, and trees will have bush shape. If gas diffusion rate is increased, tree shape is branched (Sazhin *et al* 1986). Probably, lower gas diffusion rate in specimen I occurs due to the presence of filler particles which are located in the boundaries (having low molecular density) between spherulites (with high molecular density) and to block diffusion of gases. Bush shape of trees in specimen II and lower gas diffusion are possible due to intensive partial discharges and consequently intensive gases separation. Breakdowns between electrodes occurred only in case of testing specimen II. The highest values of tree lengths were measured in these specimens (table 2).

Referring to figure 3 the high values of Q_m, measured 1 h after beginning of the testing, were observed for the specimens of unfilled and in steam crosslinked polyethylene, the low values were observed for the specimens of filled XLPE. Higher values of

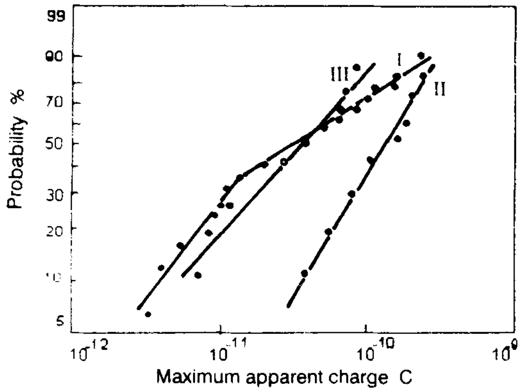

Figure 3. Distribution of maximum apparent charges in the specimens: I, II and III.

Table 3. Estimate of Weibull distribution parameters and correlation coefficients of the linear regression for measured Q_m in the specimens.

Insulation sample	Q_{m0}	β	r	Q'_{m0}	β'	r'
	C			C		
I	$2{\cdot}26\times10^{-11}$	1·245	0·977	$4{\cdot}47\times10^{-11}$	0·575	0·982
II	$1{\cdot}83\times10^{-10}$	1·263	0·990			
III	$4{\cdot}43\times10^{-11}$	0·899	0·941			

Q_m and N in insulation II than in insulation III are probably due to the larger number of gaseous microvoids in steam crosslinked insulation (Boone *et al* 1984). For the specimens II and III the empirical distributions of Q_m could be approximated by a Weibull distribution thus:

$$P(Q_m) = 1 - \exp[-(Q_m/Q_{m0})^{\beta}]. \tag{2}$$

For the specimens of filled XLPE this distribution corresponded to the distribution presented by the addition of two Weibull distributions:

$$P(Q_m) = P_1\{1 - \exp[-(Q_m/Q_{m0})^{\beta}]\} + (1 - P_1)\{1 - \exp[-(Q_m/Q'_{m0})^{\beta'}]\}. \tag{3}$$

Estimate of distribution parameters in table 3 are done.

Distribution of such type was presented (Marcek *et al* 1973; Eberhard *et al* 1984) where the tree initiation time and dielectric strength of polyethylene with additives were tested. The explanation of distribution (3) is possible on the basis of electron injection mechanism and mechanisms of inorganic filler effect. According to electron injection mechanism (Ku and Liepins 1987), the initiation of electrical trees seems to be the result of interfacial injection and extraction of electrons from a conductive point (needle tip) that projects into the dielectric. After emission into dielectric to a maximum distance of about 20 μm parallel to the field, some electrons may be trapped, some may drift out of range, and the rest will be attracted back to the electrode on the next half-cycle. During their return the electrons will be falling through a very high field and will accumulate energy. Any electron that can travel without collision for 0·1 μm in a field of 100 kV/mm will accumulate 10 eV of energy which is sufficient to ionize organic dielectric. After the absorption of sufficient energy and the decomposition of material, the dielectric will contain a cavity within which partial discharge can occur, and the breakdown will propagate as a channel, which becomes a tree. If the initial void is vented so that a supply of oxygen is available, the tree growth can proceed by both electrical and chemical (oxidative) attack.

Mechanisms of filled polyethylene tree resistance, given by Singh *et al* (1973) are based on finely divided inorganic filler present in partially crystalline polyethylene in which spherulites with high molecular density alternate with amorphous boundaries having low molecular density. The particles will locate in the boundaries where there is sufficient free volume for accommodation. As the boundaries between spherulites—which are the pathways for normal growth of electrical trees—accept particles, the resistance to propagation increases. The pathways simply become blocked with materials that are very resistant to degradation by partial discharge. Some authors (Aschraft *et al* 1976; Lobanov *et al* 1982; Eberhard *et al* 1984; Jevtic *et al* 1993) consider that polar molecules of the filler can absorb part of cinetic energy of accelerated electrons injected from an electrode under high voltage.

Therefore, the probability of occurrence of injected electrons with energy sufficient for ionization of XLPE molecules was decreased. Consequently, the probability of intensive degradation of insulation, intensive partial discharges and occurrence of Q_m (figure 3) was decreased.

4. Conclusions

Developed method of model XLPE medium voltage cable dielectric testing for partial discharge with a point to plane test geometry, enables a sufficiently exact and with small time losses, a comparative estimate of resistance of tested dielectrics (of different manufacturing methods and different contents) to electrical treeing.

The results of testing of U_i, N, Q_m and l during the initiation and growth of electrical trees reflect the technological differences of XLPE regarding manufacturing methods and contents. XLPE with inorganic filler has lower partial discharge initiation voltage but higher resistance to partial discharges and to the development of electrical trees related to XLPE without filler.

It is interesting that due to the presence of inorganic filler in XLPE the characteristic Weibull distribution of Q_m (during the growth of tree) was obtained. This distribution is presented by the addition of two Weibull distributions. Distribution of Q_m shows, in general, lower value of Q_m related to unfilled XLPE and for higher probability shows higher spread of the data (shape parameter β' of Weibull distribution is lowered).

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