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A Novel Diagnostic Method for Buried Polymer-Insulated Medium Voltage Cables

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Abstract

Depolarization currents in a large number of aged polyethylene-insulated medium voltage cables have been measured. It was found that the occurrence of a *non-linear* dielectric response is distinctive for cables containing water trees. Measurements in several sets of cable samples indicate a correlation between water tree density, degree of nonlinearity and residual breakdown strength. Furthermore, it was shown that depolarization currents can be measured under on-site conditions with simple conventional equipment. We therefore believe that the measurement of depolarization currents connected to the criterion of the 'nonlinearity' is a promising new diagnostic method for the destruction-free assessment of the state of ageing of buried cables.

1 Introduction

With the change from the classical paper-insulated to polymer-insulated medium voltage (m.v.) distribution cables unexpected problems arose due to the previously unknown slow deterioration mechanism called 'water treeing'. It is commonly accepted that water trees (wt) are responsible for many premature failures /1/. This does particularly apply to the first generation of polyethylene- (PE-) insulated m.v. cables with an outer semiconducting layer made of graphite and/or semiconductive tape. The insulation of modern triple-extruded cables has a much reduced susceptibility for the growth of water trees; nevertheless, for such cables water trees are expected to be the (only known) process responsible for the limitation of cable lifetime /2/. Therefore, utility companies have today (and will probably also have in the future) a strong need for diagnostic tools. Unfortunately, so far there are no completely reliable diagnostic methods available which allow a destruction-free assessment of the state of deterioration with respect to water treeing of the insulation of buried cables /2/.

A general approach to the search for new diagnostic methods is based on the assumption that the physico-chemical changes caused by wet ageing must result in a measurable change of the dielectric properties in a certain range of frequency (or time) and electric field strength. For reviews of investigations concerning the influence of water trees on the dielectric properties of cables and on new diagnostic methods see refs. /3/ and /2,4,5/, respectively. Of the several measurement techniques considered in our study, the measurement of depolarization currents appears to be the most promising /4,5/.

2 Dielectric Response of Cables

The polarization current is the current flowing between the electrodes of a capacitor (here a cable) after applying a potential difference between them (step response). Subsequently, after temporarily shorting the electrodes, a depolarization current can be measured in the circuit connecting the electrodes. Polarization and depolarization currents express the inability of the polarisation mechanisms in real dielectrics to follow a change of the electric field instantly. In the following we only consider 'slow' polarisation mechanisms, i.e. the measurement of the (de-) polarisation current starts about 1 s after the potential difference is applied.

2.1 Depolarization Currents

Depolarization currents in virgin and aged PE-insulated m.v. cables have been measured as a function of the magnitude of the applied electric field. Two types of behaviour have been encountered viz. *linear* and *non-linear* dielectric response /4/.

2.1.1 Linear Response

Depolarization currents in virgin m.v. cables show a linear relation between the depolarization current and the polarizing field at moderate electric field strengths, whether they are dry or saturated with water. Aged cables, which contain water trees, show a linear dielectric response only in the dry state, e.g. after drying in a oven at 70 °C for three days (see also Sect. 2.4.3).

2.1.2 Non-linear Response

In contrast to the linear behaviour described above, for many *wet-aged* cables, which contain many water trees, a more than proportional increase of the depolarization current with the previously applied electric field is observed, i.e. 'nonlinearity'.

These observations have been confirmed by numerous measurements in laboratory- and field-aged cables from different manufacturers. It is valid both for double- and triple-extruded cables. The phenomenon was observed for non-crosslinked, peroxide-crosslinked (steam- or dry-cured), silane- and electron beam-crosslinked PE cables.

2.2 Origin of Nonlinearity

Visual inspection of the cables showed a high density of bow-tie trees (btt) in all of the 'non-linear' cables. Furthermore, it was observed that the nonlinearity vanished when the cable was dried and reappeared again after wetting the cable. From these observations, it can be concluded that the non-linear dielectric behaviour is a direct consequence of the presence of bow-tie trees in the cables.

It is believed that polarization processes in the liquid phase (electrolyte) of the water trees and/or electrochemical reactions at the interface between the polyethylene and the electrolyte are responsible for the observed non-linear dielectric response. Non-linear effects can be clearly explained by the water tree model as recently proposed by Ross and Smit /6/. In their model, water trees consist of 'hydrophilic tracks running through the amorphous phase of the polymer, the hydrophilic groups being carboxylate salts bonded to the polymer and trapped inorganic salts' /6/. Under the action of an electric DC field, hydrated ions of the inorganic salts and the counter-ions of the carboxylate groups become separated and transported within the water tree. A non-linear behaviour of the resulting polarization can be explained by processes like field enhanced dissociation, hindered ion motion in the 'salt tracks' /6/ and threshold voltages of electrochemical reactions.

The influence of vented trees (vt) on the nonlinearity is not yet completely understood. This is primarily because of the sparse occurrence of vt in most field-aged cables, which makes it difficult to estimate their total number and size distribution in a larger length of cable. In some cables, which contained a very high density of very large vt we could not detect any nonlinearity, whereas in others, which contained an almost balanced number of both types of water trees, there had been indications that also vt make a contribution to the non-linear response. One possible explanation for this observation is the fact that trees grown under different conditions can have different chemical compositions /6/ and show, therefore, different dielectric properties.

2.3 Polarization Currents

In general polarization currents follow the corresponding depolarization current, whether the cable is linear or not. For longer times and higher field strengths a deviation can be seen, i.e. the polarization current decays more slowly which is a sign of the beginning of a DC-conduction regime. A 'true' DC-conduction current, which does by definition not depend on time, was hardly ever encountered. Generally speaking, we had the impression that in some cases the DC-component in the polarization current, which was not due to water trees, screened a possibly present water tree-generated nonlinearity. For this reason and because of greater ease of reliable measurement, we preferred *depolarization* to polarization current measurements.

2.4 Practical Considerations

2.4.1 Charging Times - Charging Voltages

It was experienced that the degree of the nonlinearity of a given cable is nearly the same for charging times ranging from minutes to hours. Therefore, in on-site measurements, where time is usually at a premium, charging times of only five minutes have often been chosen. The depolarization current is then measured for a period somewhat shorter than the charging time. If, e.g. in the laboratory, available time is less limited, it is preferable to charge for a longer time and to monitor the depol. current for some extended period.

As the nonlinearity usually appears around the rated voltage U_0, charging voltages from $0.5 \cdot U_0$ to $3 \cdot U_0$ are considered adequate. Above $4 \cdot U_0$, i.e. more than 10 kV/mm for standard m.v. cables, non-linear depolarization behaviour has been observed. However, these effects are rather attributed to the injection of space-charge than to water trees. In on-site measurements, polarizing voltages of U_0 and $2 \cdot U_0$ have been preferred to minimize the risk of breakdowns and to avoid arguments regarding the harm which can be done by high DC voltages to aged cables.

2.4.2 Terminations and Joints

In on-site measurements it has to be taken into account that the *sum* of the depolarization currents of the cable, the terminations and, if present, the joint(s) is measured. We found that terminations made of EPR and joints made of EPR-tapes possess a linear response, whether new or aged. Terminations made of silicone rubber may behave non-linearly, but the influence has often been found to be negligible for long cables. To avoid misinterpretations, checking may be required from case to case.

2.4.3 Drying-out of Cables

It was found that cables do not dry-out quickly, i.e. take a long time to lose their *non-linear* behaviour. In the worst case, i.e. if cables without jacket are stored in a dry and warm room, the nonlinearity is conserved at least for weeks. In the case of a fully armoured 3-phase cable, no noticeable change in the degree of the nonlinearity was observed within more than a year.

2.4.4 Exceptions

Caution has to be taken with freshly produced cables, as they may show a apparent non-linear response which is in fact caused by polarisation or transport processes of by-products of the crosslinking. To obtain reproducible results from new cables, it is often necessary to apply a conditioning process at elevated temperature for several days. In one specific case of a cable with an insulation made of a copolymer-compound we observed a persistent non-linear response (incl. polarity reversals of depolarization currents) even after long periods of conditioning. This behaviour is attributed to the higher contribution of moisture and by-products of the crosslinking to polarization and conduction in the modified polymer matrix /7/.

3 Experimental

In the laboratory depolarization currents can be measured on almost any length of cable /4,5/. If, in the lower range of cable lengths, e.g. 1 m, appropriate shielding is provided, a sensitivity of 10^{-14} A can be attained without problems. If the cable is in a state of equilibrium with its environment with respect to temperature and diffusion of moisture or volatile components, good reproducibility of measurements can be achieved.

For on-site measurements a dedicated equipment has been developed /8/. The instrument is PC-controlled and includes a 50 kV DC-supply, a logarithmic current amplifier (sensitivity 5 pA, 8 decades) and a h.v. relay. To exclude depolarization currents of the relay and the h.v. lead from the measurement, a triaxial design, the 'inner' shield being on high potential during charging, was implemented. Reduction of power-frequency noise is achieved by averaging the current and by avoiding ground loops. In this way, noise levels of some tens of pA can be reached under on-site conditions, this is sufficient for realistic cable lengths.

4 Measurements

The measurements of depolarization currents which will be reported in this Section are representative of the measurements we have made on a large number of laboratory- and field-aged cables. The main findings of the investigations will be presented by some typical examples.

4.1 Laboratory-aged Cables

Depolarization current measurements on 5 different types of cables previously subjected to accelerated ageing tests have been performed. All cables were triple-extruded XLPE-insulated 12/20 kV-class cables (5.3 mm insulation thickness). Lengths of 15 m (10 m of active length) were aged with a voltage of 36 kV at a frequency of 500 Hz. During the ageing the outer jacket of the cables was in contact with tap-water with a constant temperature of 30 °C, the stranded

Cu-conducter (95 mm^2) was filled with NaCl-solution. After 4, 8 and 12 months, 10 samples of each type were removed from the ageing facility and with 9 of them a breakdown-voltage step-test was carried out. Microscopic inspections and depolarization current measurements were made with short lengths (1 m) of the tenth sample and, for cross-checking, with the other samples after the breakdown test. Before the depolarization current measurements, all samples were kept in 90 °C water for three days to ensure uniform conditions with respect to humidity.

Tab. 1: Results of accelerated ageing tests.

Cable	Ageing time [months]	bow-tie trees / mm^3	U_{63} [kV]	$I(12kV)$ @ 100 s [pA/m]	$f_{nl} = \frac{I(24kV)}{I(12kV)}$ @ 100 s
A	0	0	218	1.5	2
	4	2'800	153	2	3.3
peroxide	8	12'200	119	1.3	9
X-linked	12	11'000	74	1.6	5.5
B	0	0	120	-	2
	4	360	100	3.5	2.3
silane	8	430	89	4.1	2.2
X-linked	12	450	97	14.2	2.3
C	0	0	222	-	-
	4	8'900	117	3.9	3
silane	8	13'700	99	6.1	3.2
X-linked	12	13'000	99	2.9	3
D	0	0	109	-	-
silane	4	1'470	76	2.9	2.3
X-linked	8	4'700	86	3.5	2.4
E	0	0	187	-	-
β	4	70	104	0.4	2
X-linked	8	150	123	0.4	2.1

The btt density shown in column 3 of Tab. 1 was determined in small sample volumes by the same person with the same technique, cross-checks with other spot samples showed reasonable agreement. Considering the difficulties in evaluating tree densities, we would like to confine our interest on the order of magnitude of the btt densities and on the ranking of the different cables. Column 4 displays the results of the step-test (5 min at 4·U_0, followed by stepwise increase by increments of U_0 of 5 min duration each, 50 Hz) in terms of 63% breakdown probabilities in a two-parameter Weibull distribution. Column 5 shows the magnitude of the depolarization current per m cable at 100 s with a polarization voltage of 12 kV. The factor f_{nl} in column 6 is a measure of the degree of the nonlinearity, it is equal to the quotient of the depolarization currents at 100 s after polarizing the cable with 12 and 24 kV, respectively, i.e. a factor of two describes a linear response. The values of some depolarization currents in Tab. 1 are missing because it proved impossible to obtain reproducible measurement in the virgin state (see Sect. 2.4.4).

From Tab. 1 it can be seen that a correlation exists between btt density and the degree of the nonlinearity, f_{nl}. The two cables A and C, showing a very high btt density, have values of f_{nl} of three or more. Cables B and D, possessing moderate densities, reveal an only slightly non-linear behaviour, i.e. f_{nl} = 2.2 ... 2.4. Finally, cable E with a very low btt density shows almost completely linear depolarization currents, i.e. f_{nl} = 2 ... 2.1. Regarding the correlation between f_{nl} and the breakdown voltage U_{63}, it can be noted that the two significantly non-linear cables A and C also show the most pronounced reduction in breakdown strength. Because of the very different breakdown voltages of the five cables in the new state, no correlation between f_{nl} and the absolute value of U_{63} can be established.

As an example, Fig. 1 shows the time behaviour of the depolarization currents of cables A and E. The cables were polarized for 30 min with 12 and 24 kV, respectively. After discharging, depolarization currents were measured during 1000 s. To check for linearity, the upper ('24 kV') curves were divided by two (curves without symbols, for cable E only visible at t > 100 s). For cable E this curve coincides with the '12 kV' data, demonstrating almost perfect linearity. Whereas the depolarization currents of cable A are obviously non-linear.

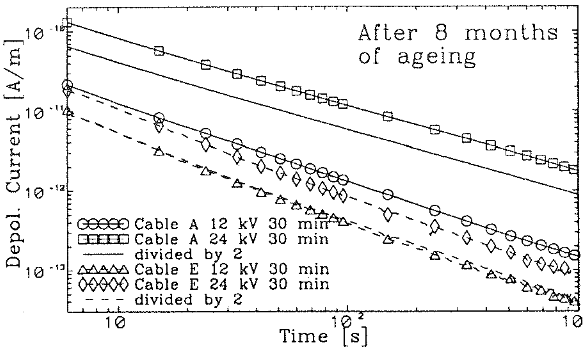

Fig. 1: Depolarization currents of cable A (non-linear, solid lines) and E (linear, dashed lines).

4.2 On-Site Measurements

4.2.1 Comparison: On-site - Laboratory

The solid lines in Fig. 2 show depolarization currents measured on-site on a buried, 17 years old, 250 m long, double-extruded, PE-insulated 6/10 kV-cable. The measurements were made after one phase of the cable had failed in service. The second phase (data not shown here) had identical depolarization currents. After these destruction-free measurements, a breakdown test was performed on-site on the two remaining phases with a mobile series-resonant test generator. The step-test (steps of 0.5·U_0 from 2.5 to 3.5·U_0, then steps of U_0 until breakdown, all steps 30 min, 45 Hz) yielded breakdown voltages of 27 kV and 33 kV for the two phases, respectively.

Subsequently the cable was extracted from the ground (as it has been laid in plastic tubes). After localizing and removing the breakdown points, depolarization current measurements were repeated six months later in the factory on the two remaining lengths of each phase. In Fig. 2 the sums of the currents of the two pieces of the same phase (dashed lines) are displayed. It can be seen that the currents are smaller than measured on-site. However, which is important to note, the *degree of the nonlinearity* was conserved. The decrease of current may be explained by the influence of temperature or a drying-out of the cable.

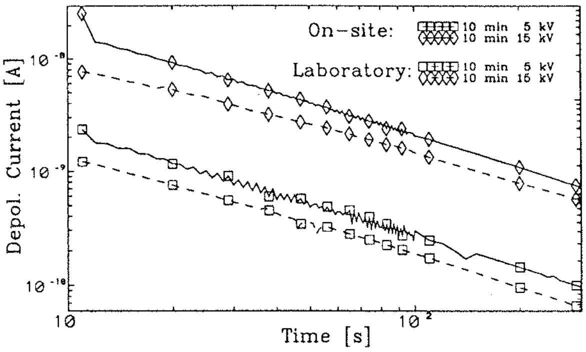

Fig. 2: Comparison of measurements on-site (solid lines) and in the laboratory (dashed lines).

Fig. 3 shows the dependence of the depolarization currents at 100 s on the previously applied charging voltage (depolarization currents after charging with voltages of 2.5, 5, 10, 15 and 20 kV have been measured on-site). An analysis of the data shows that the cable has a linear behaviour up to the operating voltage (6 kV), and then becomes gradually non-linear.

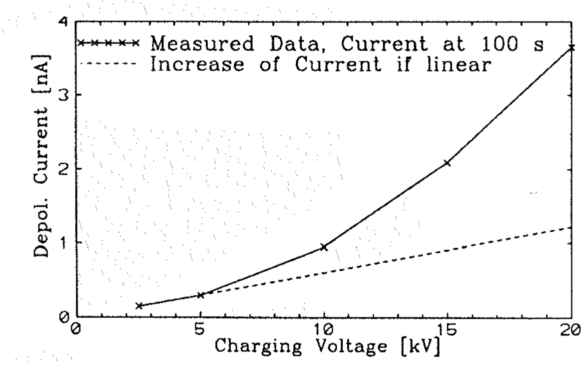

Fig. 3: Dependence of depolarization current on charging voltage.

4.2.2 Comparison: New Cable - Aged Cable

Fig. 4 shows on-site measurements of depolarization currents for a cable *nine* years in service (double-extruded 12/20 kV-PE, l = 370 m) and for a cable *two* years in service (triple-extruded 12/20 kV-XLPE, l = 378 m). The Fig. demonstrates clearly the perfectly linear response of the newer cable, whereas the older is pronouncedly non-linear. Furthermore, it can be observed that the magnitude (per unit length) and the slope of the depolarization currents do not contain any information on the state of ageing for these cables, i.e. the older cable has a smaller current. The result of the measurements is in agreement with general service experience with cables of the same type: It can be said with high probability that the insulation of the older, double-extruded cable has been degraded by water treeing. Therefore, it is expected to have a reduced breakdown strength.

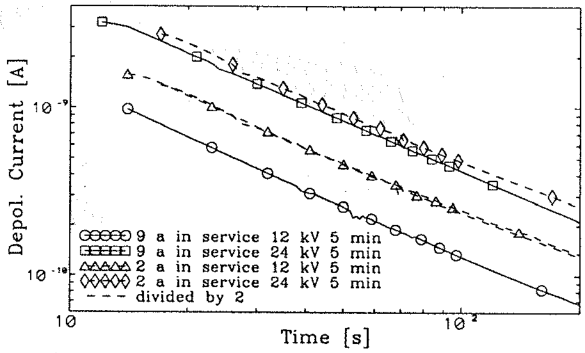

Fig. 4: Comparison of measurements on-site on 'old' (solid lines) and 'new' (dashed lines) cable.

5 Discussion and Conclusions

From the measurements presented in this paper and from many other data not shown here it can be concluded that depolarization currents of aged cables contain information about their content of water trees. It was established that:

- cables containing water trees display a *non-linear* dielectric response; the degree of the nonlinearity increases with bow-tie tree density;
- laboratory-aged cables containing a high density of btt, and thus showing a pronounced non-linear response, suffer from a more severe reduction of breakdown strength than linear cables;
- field-aged cables with a non-linear response have often a much reduced residual breakdown strength, and therefore, have to be considered as unsafe for further operation;
- the magnitude and the slope of the depolarization currents are not reliable criteria to assess the state of ageing, as they may rather depend on the chemistry (additives, by-products) and on the content of (dispersed) water.

The contribution of vented trees to nonlinearity is still uncertain, but it can be expected that at least vented trees with a similar chemical composition /6/ as bow-tie trees (i.e. containing organic and anorganic salts) also show a non-linear behaviour.

As breakdown is a stochastic process, a diagnostic method must not be expected to give precise information on the residual breakdown strength or lifetime of an individual cable. This is also true for the method described here. In other words: the often cited 'longest water tree' which is responsible for breakdown can certainly not be detected by analysing depolarization currents. However, it is believed that the measurement of depolarization currents is one of the very few available methods to assess the state of ageing of buried cables. Moreover it is believed that the analysis of the nonlinearity of depolarization currents yields *unambiguous* information on the content of (wet) *water trees* and, therefore, quite reliable information about the general state of the insulation with respect to degradation by water treeing.

The aim of future work will be to gain more experience on the behaviour of field-aged cables with regard to the nonlinearity of depolarization currents by performing further on-site measurements, and to identify the processes responsible for the non-linear dielectric response.

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