AC STRENGTH TEST DATA OF UNAGED AND WATER TANK AGED XLPE COMPOUNDS FOR TRANSMISSION AND DISTRIBUTION POWER CABLES

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ABSTRACT

AC dielectric strength tests are performed on both virgin and water filled tank aged cable model specimens insulated with four commercial XLPE compounds in order to investigate the behaviour of such material under harsh wet environments. The results are compared in terms of Weibull scale and shape parameters. The degree of deterioration of aged compounds – measured in terms of breakdown strength retention passing from unaged and aged compounds – highlights the strong influence of the formulation and the purity of the insulating compound.

INTRODUCTION

The needs of high reliability in power systems pushes power cables engineers to deepen the research in order to understand the behaviour of such components during the worst service conditions. The main effort has been to reproduce in laboratory all the possible situations that can strain a cable in terms of electrical, thermal and environmental stresses [1-14]. Cross-linked Polyethylene (XLPE) compounds and Ethylene-Propylene Rubber (EPR) compounds are nowadays the insulation for power cables mostly used in medium and high voltage systems, although EPR is limited to 150 kV cables for its own higher dissipation factor value. On the other hand the weak behaviour of XLPE insulated cables under wet conditions, in respect to EPR compounds [1,9,15], has imposed cable engineers to heighten the investigations in order to predict and quantify the decay of the electrical performances when water comes into contact with the insulation [16,17]. The utilization of a modified XLPE compound – known as water tree retardant XLPE (TRXLPE) – has partially solved the problems in medium voltage systems [8,15,16], while in the case of high voltage systems "high mesh streining" insulation materials are preferred [16], and then mechanical protection means to water ingress, as the utilization of a continuous metallic sheath, become strictly required [16,17].
In this paper four different commercial XLPE compounds are considered and their behaviour under harsh wet conditions has been investigated. The comparison between virgin materials and water filled tank aged materials with a superimposition of both electrical and thermal stress has been performed via Weibull scale and shape parameters estimated before and after ageing from AC dielectric strength data.

XLPE COMPOUNDS AND CABLE SPECIMENS

The name XLPE is generally used to represent a class of insulation compounds for cables in which a crosslinked polyethylene is the base polymer of the whole compound. In the case of medium and high voltage cables, these compounds generally consist, beside the base crosslinked polyethylene polymer, of stabilizers and a peroxide curing agent. Furthermore, the grade of cleanliness of the compound through mesh strainers is another important parameter that plays the difference under the final electrical properties of an insulation compound: smaller mesh, and then cleaner compounds, for the high voltage applications.
The four commercial XLPE compounds here considered are: one used for cable voltage ratings up to 150 kV, namely XLPE-A, and three typically used for medium voltage cables, namely XLPE-E, XLPE-F and XLPE-G.
The considered XLPE compounds are tested using cable model specimens. Such cable models, also known as mini-cables, are a scale reduction of full size cables. Since the electric performances of cable are strictly related, beside the insulation compound, to the inner and outer semiconductive layers [1,2,11,15,16], all the mini-cable used in this analysis have the same inner and outer semiconductive compound. In particular, the semiconductive compound used is a typical supersmooth copolymer blend acetylene-black trade material.
Cable model specimens are also manufactured with the same technology of full size cables, in which inner and outer semiconductive layers and the insulation layer are applied over the conductor via the triple extrusion process. Dry curing is performed in a vulcanization steel tube. Cross section dimension of the cable models are: 1.4 mm of conductor diameter (solid conductor), 0.7 mm of inner semiconductive layer, 1.5 mm of insulation layer and 0.15 mm of outer semiconductive layer.
The tested cable specimens are four meters long each. Only a length of 2 m along the central side of the specimens has been used as active length during the electrical tests. The 1 m length for each side of the specimens forms the cable terminations by removing the outer semiconductive layers and applying suitable heat shrinkable watershed terminals. Such terminations avoid surface flashover between the conductor and the outer semiconductive layer of the active length during AC electrical tests.

TEST PROCEDURES

For each insulation compound two sets of ten specimens each have been randomly selected from the respective cable reels.
Each specimen has been subjected to a preconditioning heating for 16 hours at 90 °C and 48 hours of natural cooling.
The first set of each insulation compound has been submitted at dielectric strength test, while the second one has been aged in a water filled tank. Test procedure of both

dielectric strength and ageing in water filled tank are described in the following subsections.
Dielectric strength tests on unaged and aged cable specimens are performed in order to evaluate the degree of deterioration in the cable dielectric material due to ageing. The degree of deterioration is then assumed to be directly proportional to the amount of ageing by which the dielectric strength falls below that of an unaged cable [10,16]. In this paper the degree of ageing it is also reported in terms of percentage retention of unaged cables dielectric strength.

Dielectric strength test procedure

Each specimens is tested at AC dielectric strength applying a 2 kV/s 50 Hz rising voltage up to breakdown. The voltage is applied between the cable conductor and the active length of the specimen immersed in a tap water filled tank at room temperature. Contingent breakdowns outside of the specimen active length (along the terminations held outside of the water) impose the rejection of the specimen under test.
All specimens subjected to dielectric strength test show no breakdown along the specimen ends. All breakdowns have been registered along the active length of the specimens.
Each set of cables has shown a good fitting to the two-parameter Weibull distribution, confirmed by three goodness of fit tests for Weibull distribution [18]. Consequently, after the dielectric strength test, each set of cable is represented by its scale (α) and shape (β) parameters of the Weibull distribution. The scale parameter is usually referred as characteristic dielectric strength, while the shape parameters is inversely proportional to variance of the dielectric strength data. The estimation of the Weibull parameters are performed with the suitable estimator to be used even in presence of possible outliers in the test data [19,20].

Water filled tank ageing test procedure

The set of cables subjected to ageing have been laid in a tank filled with tap water. The conductor of each specimen has been stretched at both ends in order to obtain an interstice between the conductor and the inner semiconductive layer. Such interstice has been filled and maintained with deionized water for all the ageing long in order to obviate corrosion of the conductor. On the other hand the utilization of tap water in the conductor leads to a possible growth of a corrosion film that can cause water blockage resulting in alternate dry and wet sections along the conductor [10]. In this case the test simulate both the transversal (water outside the cable) and longitudinal (water along the conductor) possible penetration of water in the insulation wall that a full size cable can incur during its service life. In such harsh environment the cable is maintained for 1000 hours (about 42 days) with a conductor temperature of 85 °C, the water in the tank at 70 °C and a maximum electric field of 9 kV/mm applying a voltage between the conductor of the cable and the water in the tank. Conductor temperature is kept up at the fixed temperature range via the induce current method.
Each specimen subjected to water filled tank ageing test procedure has not reached the breakdown within the 1000 hours of ageing, consequently they all have been subjected to the dielectric strength test procedure.

DISCUSSION OF RESULTS

The estimated values of the scale (α) and shape (β) parameters of Weibull distribution are reported in Table I for both unaged sets of cable and for water filled tank aged sets of cable, in the following simply named as aged for brevity.
Examining the unaged specimens it is possible to highlight the higher performances of XLPE-A compound: the scale parameter is about 72 kV/mm higher than that of XLPE-E and XLPE-F and 55 kV/mm higher than that of XLPE-G. Furthermore, XLPE-A compound has even the highest value of the shape parameter: about two units higher than the other three compounds. As expected XLPE-A has higher performance than the other three compounds because it is used also for high voltage cables, while the other compounds are usually selected for medium voltage cables.
XLPE-E, XLPE-F and XLPE-G compounds have very similar scale and shape Weibull parameters: the scale parameter is in the range of 65÷82 kV/mm and shape parameter in the range of 3.2÷3.8. Although XLPE-E and XLPE-F comes from different manufacturers, they have quite the same values of both scale and shape parameters.

Table I.
Scale (α) and shape (β) parameters of both unaged and aged sets of cable

Type of compound		α [kV/mm]	Δα [kV/mm]	β	Δβ
XLPE-A	Unaged	137.2	107.8	5.6	-4.1
	Aged	29.4		9.7	
XLPE-E	Unaged	65.7	25.7	3.5	-4.6
	Aged	40.0		8.1	
XLPE-F	Unaged	64.6	32.9	3.8	-19
	Aged	31.7		22.8	
XLPE-G	Unaged	82.5	52.6	3.2	-6.1
	Aged	29.9		9.3	
$\Delta\alpha = \alpha^{Unaged} - \alpha^{Aged}$ $\Delta\beta = \beta^{Unaged} - \beta^{Aged}$					

Higher values of the shape parameter means a reduced variance of the test data and consequently a higher degree of homogeneity of the compound. This fact reflects a reduced decay of the breakdown voltage with cable length [21], and in terms of full size cables it points out higher insulation performances. Insulation compounds with higher values of the shape parameter have positive influence in insulation coordination of cable lines [22].
If the scale parameter values estimated from dielectric strength tests on aged specimens are considered, it is possible to note that:

- the insulation compounds that have the highest values when unaged (XLPE-A and XLPE-G) are subjected to the strongest reductions;
- the values range between 30 and 40 kV/mm for all compounds: in particular 40 kV/mm for XLPE-E and about 30 kV/mm for the other three compounds.
- in respect to the unaged value the scale parameter reduces at 21% for XLPE-A, at 61% for XLPE-E, at 49% for XLPE-F and at 36% for XLPE-G;

Evaluating the shape parameter values of aged specimens, it can be asserted that:

- the shape parameter increases: this fact reflects a higher homogeneity of the insulation to the breakdown after ageing;

- except for XLPE-F in which the values is very high (22.8), the other compounds have a shape parameter value ranging between 8.1 and 9.7.

XLPE-A and XLPE-G have the largest reduction of the characteristic dielectric strengths and then they seems to age more quickly in respect of XLPE-E and XLPE-F; this condition let suppose that the polymer matrix of both XLPE-A and XLPE-G is more vulnerable to hydrolytic attack.

XLPE-E and XLPE-F have lower characteristic dielectric strengths and a dielectric strength retentions higher than XLPE-A and XLPE-G, this facts let to suppose that:

- the stabilizers contained in XLPE-E and XLPE-F compounds have also treeing retardant characteristic properties in respect to XLPE-A and XLPE-G compounds, although all the compounds here considered are not traded as TR-XLPE compounds; for example, stabilizers with a greater quantity of ionic contents, although they yield the polymer more hydrophilic, they impart a higher resistance to water tree growth and consequently a higher performance to dielectric strength under water aged specimens [15];
- the mesh grade of XLPE-E and XLPE-F compounds are lower than XLPE-A and XLPE-G ones; this fact explains the lower characteristic dielectric strength of unaged XLPE-E and XLPE-F due their higher content of impurities; on the other hand such impurities, if polar, can act as treeing retardant improving the ageing under harsh wet environment. Furthermore higher quantity of impurities of less mesh strained compounds can sometime have an advantageous effect under wet conditions imparting a higher resistance to water tree growth.

Higher values of the shape parameter can be explained that the ageing effect due to water filled tank is not a "discrete" phenomenon within the dielectric [15], but it uniformly acts in the entire dielectric, and then it can be view as a "bulk" phenomenon that produces relatively small variance in dielectric strength test data.

In Figg. 1 and 2 scale and shape parameters estimated values and their 90% two-sided confidence limits [23] for both unaged and aged sets of cable are plotted.

Impulsive dielectric strength tests performed on different XLPE and EPR compounds [12,24] from the authors show that there is not always an increase of the Weibull distribution shape parameter passing from unaged to aged sets of specimens.

As in the case of AC strength tests, insulation compound XLPE-A, with the same cable models but different semiconductive compound layers, has been investigated at impulsive standard lightning wave shape [24]. The 1.2/50 μs impulsive dielectric strength tests were performed on unaged specimen with both positive and negative impulse polarity. Table II shows the scale and the shape Weibull parameters estimated after impulsive and AC dielectric strength tests on XLPE-A compound. Although, such results are not completely comparable because of the sets of cable models used on impulsive and AC dielectric strength tests have different semiconductive compounds, they can give an order of magnitude of the behaviour of unaged XLPE-A compound under different electrical stress.

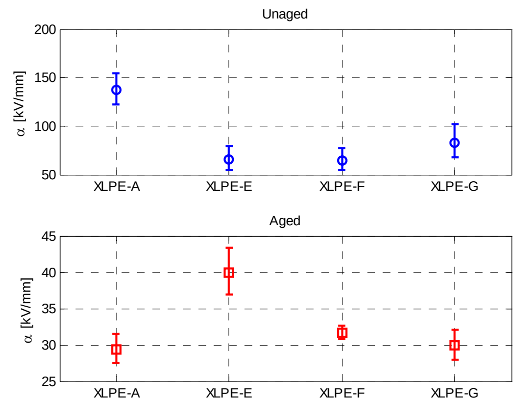

Fig. 1. Two side confidence limits at 90% of scale Weibull parameter for unaged and aged sets of specimen.

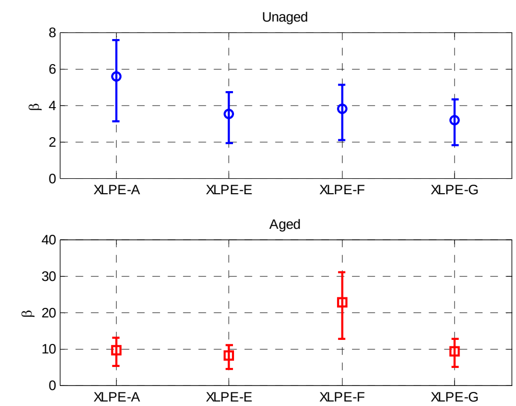

Fig. 2. Two side confidence limits at 90% of shape Weibull parameter for unaged and aged sets of specimen.

Table II
Scale (α) and shape (β) Weibull parameter at both standard lightning wave shape (after [24]) and AC dielectric strength test on cable models insulated with XLPE-A compound

	α [kV/mm]	**β**
+ 1.2/50 μs room temp.	197.3	13.8
- 1.2/50 μs room temp.	310.3	10.1
+1.2/50 μs 90 °C temp.	167.2	4.8
-1.2/50 μs 90 °C temp.	180.5	14.1
AC room temp.	137.2	5.6

Such table highlights that the scale parameter values estimated from impulsive dielectric strength test data are higher than AC data. At room temperature, impulsive characteristic dielectric strength is more than twice (2.2 times) with negative polarity and more than 1.4 times with positive polarity in respect to the AC characteristic dielectric strength. This fact confirms the rule of thumb that the AC strength is generally about half of the impulsive strength.

The shape parameter is higher for impulsive dielectric strength data, except in the case of positive polarity with the specimens tested at 90 °C temperature.

CONCLUSIONS

The analysis of the results of dielectric strength tests performed on unaged and water filled tank aged cable model specimens manufactured with four different commercial XLPE compounds reveals that:

- the compounds with the highest characteristic dielectric strengths when unaged have the highest reduction after ageing;
- the characteristic dielectric strength retention ranges between 21% and 61% of the initial (unaged) values;
- the characteristic dielectric strength values range between 65 and 137 kV/mm before ageing and between 30 and 40 kV/mm after ageing;
- the shape parameter always increases after ageing; it is lower than 6 before ageing and higher than 8 after ageing.

The comparison between impulsive and AC dielectric strength test data seems to confirm the rule of thumb that the impulsive strength is about twice the AC strength.

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