Energy 34 (2009) 245–253

Contents lists available at ScienceDirect

Energy

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

Crossing quantities: How to compare electrical strength performances of insulation compounds for power cables

M. Marzinotto [a,*], G. Mazzanti [b], C. Mazzetti [a]

[a] Electrical Engineering Department, Sapienza University of Roma, Via Eudossiana 18, 00184 Roma, Italy
[b] Electrical Engineering Department, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

ARTICLE INFO

Article history:
Received 27 June 2007
Available online 19 September 2008

Keywords:
Cable lines
Breakdown voltage
Dielectric strength
Enlargement law
EPR insulation compounds

ABSTRACT

An innovative theory—derived from the “enlargement law”—about how to compare the breakdown performances of power cable insulation compounds is illustrated and applied herein. This theory enables the selection between two different compounds candidate for the insulation of power cables via dielectric strength tests performed on cable models. In particular, compound performances are investigated vs. cable length looking for the so-called crossing length, i.e. a crossover point between the performances of the two compounds, such that one of the two performs better above this length, and conversely the other below it. The application of this theory consists in a comparison between two EPR compounds, based on lightning impulse breakdown tests realized on mini-cables, and shows that the crossing length depends strongly on cable size and voltage rating. Therefore, the practical selection of the best compound must consider the typical installation lengths of real cables.

Finally, the relationship between crossing quantities and failure probability is analyzed, highlighting that while crossing length does depend on failure probability, crossing strength and breakdown voltage do not. Thus, since crossing strength depends mainly on compounds Weibull parameters, it is the key for comparing the intrinsic breakdown characteristics of competing compounds.

1. Introduction

In the framework of the experimental activities supporting the characterization of power cable insulation and the design of medium voltage (MV) and high voltage (HV) cables, a common practice consists in performing dielectric strength and accelerated life tests on small-size cable models, extrapolating subsequently the relevant results to full-size cables. This practice involves remarkable advantages, i.e. the ease of sample preparation, the chance of employing small test facilities and the simplicity of test procedures, thereby implying dramatic time and money savings.

The extrapolation of cable model test results to full-size power cables requires reliable extrapolation tools, capable of predicting the statistical behavior of large insulation systems on the basis of the performances of the elemental insulating portions that compose the whole insulation thickness and length. The most popular among these tools is the well-known “enlargement law”, a practical application of the multiplication law for non-dependent probabilities in the framework of Weibull statistics [1,2]. Though the enlargement law is very powerful, its application requires care, particularly when power cables have much thicker and longer insulation than cable models.

In [3–8], some fundamental theoretical considerations required for a proper application of the “enlargement law” are developed and, in particular, attention is focused on the comparison between the dielectric strength of two different solid-extruded compounds and on the dependence of dielectric strength on cable length. These theoretical arguments show that a crossover may exist between the performances of two compounds exhibiting—according to dielectric strength tests performed on cable models—different values of dielectric strength, as well as of shape parameter of the Weibull distribution of dielectric strength. This crossover occurs at a given value of cable length, referred to as “crossing length”; its existence depends on the value of Weibull shape parameter, thereby highlighting the essential role played by such parameter in the selection of the best insulation for a power cable of given voltage rating and fixed length, and emphasizing the need for its careful estimation.

In this paper, the theory of the enlargement law is briefly recalled in Section 2. The relevant considerations about the comparison between the dielectric strength of two different solid-extruded compounds, previously illustrated in detail in [3–8], are recalled in Section 3. Then, in Section 4 all these theoretical arguments are applied for a comparison between two different ethylene-propylene rubber (EPR) compounds candidate for the

---

* Corresponding author. Tel.: +39 06 44585544; fax: +39 06 4883235.
E-mail addresses: maxmarzinotto@ieee.org, carlo.mazzetti@uniroma1.it (M. Marzinotto), giovanni.mazzanti@mail.ing.unibo.it (C. Mazzetti).

0360-5442/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2008.07.011

realization of full-size cables. On the basis of the results of lightning impulse dielectric strength tests carried out on small-size cable models [9,10], the length effects and the existence of the above-mentioned crossing length for different voltage ratings (i.e. 20 and 150 kV) of the full-size cables are investigated. The practical significance of the crossing length when compared to typical installation lengths of real cables is discussed. New theoretical developments relevant to the crossing quantities and related to the percentiles of the breakdown voltage are reported in Section 5. The relevant conclusions about the guidelines that can be drawn for the choice of the best compound, close the paper.

2. The enlargement law

The "enlargement law" relates the breakdown test results (i.e. breakdown voltages and times) relevant to small-size specimens to large-size insulation, by accounting for time and volume effects associated with the insulation arrangement. Indeed, due to the inherent inhomogeneities of solid-extruded dielectric materials, a larger number of weak points is found in larger-size insulation rather than in smaller-size insulation, and this yields lower breakdown times and voltages in the former than in the latter. In the case of power cables, time and volume effects (contemplated in the enlargement law), essential for the insulation design, are considered on the basis of laboratory test results stemming from cable models or short lengths of full-size cables, for the reasons outlined in Section 1.

Time and volume effects are taken into consideration by the following enlargement factor N:

$$N = \frac{V_2 T_2}{V_1 T_1} \tag{1}$$

where V_2 and T_2 are, respectively, enlarged or reduced states of volume and time, while V_1 and T_1 are the corresponding initial states. The enlargement factor N reduces simply to the consideration of "volume effects" when $T_1 = T_2$: this is the case of dielectric strength tests on single insulating components or insulating models, in which only breakdown values are taken into consideration. N can be reduced to a "time effect" when breakdown-time tests (often referred to as accelerated life tests) are performed on large insulation arrangements and no volume enlargement is needed ($V_1 = V_2$).

The application of the "enlargement law" to a generic failure probability distribution leads to the following general relationship [1]:

$$F_2(x;\Theta_2) = 1 - \exp\left[\frac{1}{V_1 T_1}\iint_{V_2,T_2} \ln[1 - F_1(x;\Theta_1)]\,\mathrm{d}v\,\mathrm{d}t\right] \tag{2}$$

where F_2 is the cumulative probability of failure in the enlarged state; F_1 is the cumulative probability of failure of the generic differential small element ($\mathrm{d}v$,$\mathrm{d}t$); $\boldsymbol{\Theta}_1$ and $\boldsymbol{\Theta}_2$ are the parameters vectors of the initial state distribution and final state distribution, respectively.

Dielectric strength tests and accelerated life tests performed on polymeric insulating materials provide data that well fit the two-parameter Weibull distribution [1–23], thus with $\boldsymbol{\Theta}_1 = (\alpha_1, \beta_1)$:

$$F_1(x;\Theta_1) = 1 - \exp\left[-\left(\frac{x}{\alpha_1}\right)^{\beta_1}\right] \tag{3}$$

where α_1 and β_1 are the scale and the shape parameter of the distribution.

Let us consider only volume enlargement ($V_1 \to V_2$) and consequently no time effect ($T_1 = T_2$), and replace (3) in (2), taking into account that for power cables such enlargement relates to a cylindrical geometry, that involves no changes in field strength radial distribution along the main dimension of the system (e.g. along cable length). This yields (as extensively illustrated in [4]):

$$F_2(x;\Theta_2) = 1 - \exp\left[-\left(\frac{x}{\alpha_2}\right)^{\beta_2}\right] \tag{4}$$

with $\beta_2 = \beta_1$.

Eq. (4) outlines that the final state distribution in this case is still a two-parameter Weibull distribution where the shape parameter is the same of the initial distribution, thus $\boldsymbol{\Theta}_1 = (\alpha_1, \beta)$ and $\boldsymbol{\Theta}_2 = (\alpha_2, \beta)$ where the relationship between α_1 and α_2 is

$$\frac{\alpha_1}{\alpha_2} = \left(\frac{L_2}{L_1}\right)^{1/\beta}\left(\frac{r_{i2}}{r_{i1}}\right)^{2/\beta}\left[\frac{(r_{a2}/r_{i2})^{2-\beta} - 1}{(r_{a1}/r_{i1})^{2-\beta} - 1}\right]^{1/\beta} \tag{5}$$

where L_1 is the length of the cable tested in laboratory; L_2 is the length of the cable installed in field; r_{i1} and r_{a1} are, respectively, the inner and outer insulation layer radii of the cable tested in laboratory; r_{i2} and r_{a2} are, respectively, the inner and outer insulation layer radii of the cable installed in field.

For the application of such enlargement law is fundamental that the cable installed in field (final state of the enlargement process) is made with the same materials and the same technologies of the cable tested at dielectric strength test in laboratory (initial state of the enlargement) [3–9,15,17,20,22,23].

Eq. (5) is of paramount importance in what follows.

The dielectric strength at 63.2% failure probability of full-size cables (α_2) estimated by means of (5) can be related to the breakdown voltage at 63.2% failure probability via the well-known formula:

$$V_2 = \alpha_2 r_{i2} \ln\frac{r_{a2}}{r_{i2}} \tag{6}$$

Both the dielectric strength and breakdown voltage at 63.2% failure probability are used as reference values, since they represent the scale parameters of the Weibull distribution of dielectric strength values and breakdown voltage values, respectively.

3. Crossing breakdown voltage and crossing length of two cable lines

Let us consider two sets of cable models, both subjected to laboratory dielectric strength tests and differing only in the insulation compound: let the first set (set A) be manufactured with "compound A" and the second set (set B) with "compound B". Let us define as α_{1A} and β_A the scale and shape parameters of the Weibull probability distribution of dielectric strength values relevant to cable model set A, and similarly α_{1B} and β_B the scale and shape parameters of the Weibull distribution of dielectric strength values relevant to cable model set B. The application of the enlargement law (5) for calculating the scale and shape parameters of the Weibull probability distribution relevant to a full-size cable yields α_{2A} and β_A (β parameter does not change with the enlargement) for a full-size cable manufactured with insulation compound A, and α_{2B} and β_B for a full-size cable manufactured with insulation compound B.

It is interesting to illustrate the kind of variation of α_{2A} and α_{2B} with cable length that can be obtained by means of the enlargement law, by resorting to two parametric examples. In these examples, cable model and full-size cable geometries are fixed, while the couple of considered compounds A and B varies, together with the relevant values of dielectric strength obtained