Reliability of HVDC cables: the role played by the enlargement law

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ABSTRACT

In this paper the effect of the enlargement law on the reliability of HVDC cables is discussed. In order to do that an innovative theoretical approach for extending to DC cables the traditional enlargement law valid for AC cables is illustrated: the approach takes into account some aspects peculiar of dielectrics under DC stress. An application of the novel enlargement law developed is given in the paper considering real HVDC cables and examining the influence of some of the many parameters appearing in the model.

KEYWORDS

HVDC cables; Insulation; Reliability; Volume effect; DC Electric field.

INTRODUCTION

High Voltage Direct Current (HVDC) systems have gained an important role in the interconnection of islands and border countries due to their technical and economic advantages, that are particularly evident over long links. Furthermore, in the recent years Transmission Systems Operators (TSOs) approach more and more to land domestic HVDC interties with the aim to have "tapped corridors" within an High Voltage Alternate Current (HVAC) meshed grid.

So far HVDC cables have found their application especially with paper-oil insulation, particularly Mass Impregnated Non-Draining (MIND) type, more widely used than the oil filled type (both low and high pressure) and an obliged solution in very long submarine links. Nevertheless recently the research and development in extruded insulations for DC application [1-3] has led extruded cables to be competitive in both land and submarine HVDC interties for higher and higher voltages and powers.

Due to the inherent inhomogeneities in the insulation, the reliability of such long cables is significantly influenced by the volume effect related to the enlargement between laboratory-tested cables – both at the R&D stage and at the qualification stage – and full-size full-length cables installed in the field. For this reason, accounting properly for the effect of this enlargement on the test and design voltage selection is mandatory in order to ensure satisfactory long-term reliability of HVDC cables. This can be done resorting to the well-known enlargement law, that however has been traditionally developed for HVAC cables, and has thus to be recast for HVDC cables. A proposal about this extension of the enlargement law from HVAC cables to HVDC cables has been put forward by the authors in previous investigations [4-6].

However, it must be pointed out that this extension is not a trivial matter. Indeed, as well known, despite large

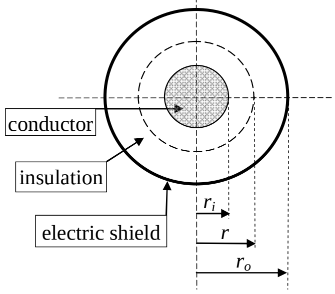

Fig. 1. Sketch of the cross-section of the insulation of a coaxial cable

similarities in the formation of HVDC cables with respect to HVAC cables, the electric stress in the insulation wall is very different: resistive in the former, capacitive in the latter. Consequently, the statistical enlargement law over the volume of insulation [7,8], which has demonstrated its interesting application on AC cables to infer statistically the breakdown performance of cable lines starting from breakdown test results performed in short lengths of cables in laboratory [9-11], has to be adapted to DC cables. From this respect, as previously emphasized, HVDC cable lines are usually very long compared to HVAC cable lines, thus the volume effect in the enlargement law plays a much more important role in the former than in the latter.

Moreover, it must be outlined that in DC cables space charges may alter the electric field profile evaluated analytically [2,3,12], that however remains in practice an essential reference for the design of HVDC cables. For this reason, since the distribution of space charges in DC insulation can be assessed through measurements only, they are not considered here.

Coming to the electric field profile within the insulation, let us consider a length *l* of a coaxial cable, whose cross-section – sketched simply in Fig. 1 – can be characterized by the inner and the outer radii of insulation, r_i and r_o respectively, and by the generic radial coordinate *r*. When an rms AC voltage V_{AC} is applied to such a cable, a capacitive field develops in the cable geometry, that can be easily calculated under the assumption (acceptable in practice) that the electrical permittivity, ε, of the insulation is constant with temperature – thus it remains constant across the dielectric as the cable is loaded. Then, the AC electric field $E_{r,AC}$ at any radius *r* within the dielectric is given by the following well-known relationship:

$$E_{r,AC} = \frac{V_{AC}}{r \ln(r_o / r_i)} \quad (1)$$

that shows how $E_{r,AC}$ depends only on inner and outer insulation radii, as well as on radial coordinate r and applied AC voltage between conductor and screen, V_{AC}.

On the contrary, when a DC voltage V_{DC} is applied to such a cable the voltage gradient depends on the conductivity of the insulation, which in turn is a function of the local temperature and also (though less markedly) of the local electric field [2,3,12]. Therefore, when the insulation is subjected to a temperature gradient due to current flow and Joule heating in the conductor, the electric field distribution inside the insulation changes significantly compared to the isothermal cable, giving rise to the so-called voltage inversion of electric field in HVDC cables. It can be shown that the DC electric field $E_{DC}(r)$ at radius r within the dielectric can be expressed via the following simplified relationship [2,3,12]:

$$E_{r,DC} = \frac{\delta V_{DC}(r/r_o)^{\delta-1}}{r_o[1-(r_i/r_o)^{\delta}]} \qquad (2)$$

where δ is equal to:

$$\delta = \left[\frac{aW_C}{2\pi\lambda_{T,d}} + \frac{bV_{DC}}{(r_o - r_i)}\right] / \left[\frac{bV_{DC}}{(r_o - r_i)} + 1\right] \qquad (3)$$

being W_C=conductor losses (W/m), $\lambda_{T,d}$ = thermal conductivity of insulation (W $m^{-1}K^{-1}$), a= temperature coefficient of electrical resistivity (K^{-1} or $°C^{-1}$); b= electrical stress coefficient of electrical resistivity (m/MV or mm/kV).

The field distribution of (2) affects strongly the way the cable is designed, as well as the extrapolation of breakdown test results from laboratory specimens to full-size cables, that – for HVAC cables – is commonly performed by the well-known "enlargement law" [7,8]. Such a law is strongly affected by the field profile and should be changed properly in order to account for the DC field profile. This was done carefully in [4-6].

In this paper the relationship between cable insulation reliability and the enlargement law is clarified first resorting to Weibull statistics. Then, the traditional enlargement law for coaxial AC cables is reviewed in order to show how it can be extended to HVDC cables by means of an innovative theoretical approach. This approach is shown in detail thereafter, by taking into account some aspects that are peculiar of HVDC cables, namely [2,3]:

1) the dependence of (2) not only on geometry (inner and outer radii of the insulation, as in the AC case), but also on the volume electrical resistivity of the insulation;
2) the associated dependence of the volume electrical resistivity of insulation on electric field and temperature;
3) the role played by the heat dissipated through the different cable layers;
4) the role played by insulation thermal resistivity.

An illustrative application of the enlargement law model developed in this paper is finally given, by considering real HVDC cables and examining the influence of some of the various parameters that appear in the model.

WEIBULL STATISTICS AND RELIABILITY MODELS FOR CABLE INSULATION

The broad theoretical and experimental literature about the endurance of dielectrics – particularly of the polymeric type - highlights that the life of cables subjected to high voltage and temperature should be estimated by means of electro-thermal life models [12]. Indeed, such models express insulation life as a function of both electric field and temperature. By this way, the fundamental role played by electrical stress and by the synergism between electrical and thermal stress in insulation aging is considered.

An exhaustive review of electro-thermal life models valid for different insulating systems can be found in [13]. For polymeric insulation of HVAC cables, a model holds within typical test and service ranges of electrical and thermal stress. This model is the combination of two popular single-stress models, i.e. the Arrhenius model for thermal life and the Inverse Power Model (IPM) for electrical life, and can be written as [13,14]:

$$L = L_0 (E/E_0)^{-(n_0 - b_L cT)} \exp(-B_L cT) \qquad (4)$$

where E is maximum electric field, cT=1/T_0-1/T is the so-called conventional thermal stress (T being maximum temperature in Kelvin degrees and T_0 a proper reference temperature, commonly that of the ambient), n_0 is the so-called Voltage Endurance Coefficient (VEC) at T=T_0, E_0 is a value of electric field below which electrical aging is deemed as negligible, L_0 is life at T=T_0, E=E_0, B_L is equal to $\Delta W/k$ (ΔW being the activation energy of the main thermal degradation reaction and k being the Boltzmann constant) and b_L is a parameter that rules the synergism between electrical and thermal stress. Model (4) was applied in [15,16], to HVAC EPR- and XLPE-insulated cables. The same model can be employed also for HVDC cables, as done e.g. in [17,18], as well as in [19] - as to the electrical part of the model – where a value of n_0=10 is assumed. Other electro-thermal life models can be employed both for HVAC cables - as done in [16] – and for HVDC cables (see e.g. [12]) provided that they are fully-explained as a function of applied stresses (as (4)) and hold for the cable insulation that is being analyzed.

It must be emphasized that, according to the modern probabilistic approach to power system component design, time-to-failure L in relationship (4) should be always regarded as relevant to a given failure probability, P. The cumulative probability distribution function (cdf) that is commonly used for associating time-to-failure with failure probability in the case of extruded polymeric insulation for power cables is the Weibull cdf [7], namely:

$$P(t_P; E, T) = 1 - \exp\{-[t_P/\alpha_t(E,T)]^{\beta_t}\} \qquad (5)$$

Close and Return

where t_P is the 100P^{th} failure-time percentile, i.e. life at probability P. $\alpha_t(E,T)$, the 63.2th failure-time percentile, is the scale parameter of the cdf and is a function of applied stresses, while β_t is the shape parameter of the cdf[1].

Thus, the reliability at mission time t_P can be trivially evaluated from (5) as $R(t_P;E,T)=1-F(t_P;E,T)$. Moreover, the relevant failure rate can be estimated through the following hazard function $h(t_P;E,T)$ [7]:

$$h(t_P;E,T) = \frac{\beta_t}{\alpha_t(E,T)}\left[\frac{t_P}{\alpha_t(E,T)}\right]^{\beta_t-1} \quad (6)$$

Scale parameter α_t in (5) can be expressed through a proper electro-thermal life model relevant to 63.2% failure probability, e.g. model (4). Then, the following probabilistic life model (i.e. a relationship between life, failure probability and stresses for an insulation of given size [15,16] is obtained:

$$t_P = \left[-\ln(1-P)\right]^{1/\beta_t}\alpha_0\left(E/E_0\right)^{-(n_0-b_L cT)}\exp\left(-B_L cT\right) \quad (7)$$

α_0 being the value of L_0 at 63.2% failure probability, and reliability can be evaluated conversely as:

$$R(t_P;E,T) = \exp\left\{-\left[\frac{t_P}{\alpha_0\left(E/E_0\right)^{-(n_0-b_L cT)}\exp\left(-B_L cT\right)}\right]^{\beta_t}\right\} \quad (8)$$

Within this probabilistic framework, the reliability of a full size cable can be evaluated on condition that model parameters derived from tests performed on specimens (e.g. cable models) can be extrapolated to power cables by accounting for the different volume of tested objects with respect to full-size insulation. It can be shown that parameters n_0, b_L, B_L, β_t do not change in the enlargement process, being inherently characteristic of the material rather than of the dimension of the insulation. On the contrary the scale parameter α_0 of the Weibull distribution is affected by the different volume of tested objects with respect to full-size insulation, through the so-called statistical "enlargement law" [7]. The "enlargement law" is a relationship that expresses the enlargement in terms of the scale parameter α_0 of the Weibull distribution with respect to volume. The next Section illustrates the "enlargement law" in the case of a HVAC cable – where the electric field distribution within insulation thickness is always of the capacitive or "Laplacian" type (see (1)) – as a propedeutic case to the extension of this law to HVDC cables, done in the further Section.

1 Also β_t may depend on E, T, but such dependence is mostly weaker than that of α_t [13,14]. Hence, it is omitted here for the sake of simplicity.

THE ENLARGEMENT LAW FOR HVAC CABLES

The "enlargement law" can be evaluated with respect to volume. This is taken into consideration by the enlargement factor N [6,7]:

$$N = V_N / V_1 \quad (9)$$

where V_N is the enlarged or the reduced state of volume, while V_1 is the volume initial state.

This is the case of dielectric strength tests on single insulating components or insulation system models, in which only breakdown values are taken into consideration. The application of the enlargement law to a generic distribution leads to the following general form [7,8]:

$$F_N = 1-\exp\left[\frac{1}{V_1}\int_{V_N}\ln[1-F_1(x,\alpha,\beta)]dv\right] \quad (10)$$

where F_N is the distribution in the enlarged state, F_1 is the distribution of the generic differential element in volume dv, α and β are the generic parameters of this distribution.

As pointed out above, breakdown tests performed on both HVAC and HVDC polymeric insulating materials provide data that well fit the 2-parameter Weibull distribution. The application of (10) to a length l of cable insulation – with cross section sketched in Fig. 1 – under the constant-time hypothesis plus the Weibull hypothesis for F_N yields the following relationship:

$$F_N = 1-\exp\left\{\frac{1}{V_l}\int_{r_i}^{r_o}[-(E_r/\alpha_l)]^{\beta}2\pi r l dr\right\} \quad (11)$$

where α_l is the Weibull scale parameter of dielectric strength relevant to the generic differential element of length dl comprised between r and $r+dr$, and E_r denotes the electric field within the insulation at radial coordinate r. Such a field E_r for an AC cable having the purely radial geometry depicted in Fig. 1 coincides with field $E_{r,AC}$ expressed by (1), that can be trivially rewritten for the field at the inner radii, r_i, as follows:

$$E_{r,i} = \frac{V_{AC}}{r_i\ln(r_o/r_i)} \quad (12)$$

From relationships (1), (11) and (12), after several manipulations reported in detail in [7,8], the well-known enlargement law for coaxial AC cables is obtained, namely [7-10]:

$$\frac{\alpha_1}{\alpha_2} = \left(\frac{L_2}{L_1}\right)^{1/\beta} \left(\frac{r_{i2}}{r_{i1}}\right)^{2/\beta} \mathrm{H}_{AC}(r_{i1}, r_{i2}, r_{o1}, r_{o2}) \quad (13)$$

$$\mathrm{H}_{AC}(r_{i1}, r_{i2}, r_{o1}, r_{o2}) = \left[\frac{(r_{o2}/r_{i2})^{2-\beta} - 1}{(r_{o1}/r_{i1})^{2-\beta} - 1}\right]^{1/\beta} \quad (14)$$

where: α_1, L_1, r_{i1} and r_{o1} are respectively dielectric strength at 63.2 %, length, inner and outer insulation layer radii of a "small" cable (e.g. a cable model) denoted as "cable 1"; α_2, L_2, r_{i2} and r_{o2} are respectively dielectric strength at 63.2 %, length, inner and outer insulation layer radii of a "large" cable (e.g. a full-size power cable) denoted as "cable 2". Note that the expression of H_{AC} holds for $\beta \neq 2$.

THE NEW ENLARGEMENT LAW FOR HVDC CABLES

When dealing with HVDC cables, a similar procedure to that employed for AC cables can be applied for the derivation of the enlargement formula. The starting point is once more equation (11), where now field E_r coincides with field $E_{r,DC}$ expressed by (2), that can be rewritten for the field at the inner radii, r_i, as follows:

$$E_{r,i} = \frac{\delta V_{DC}(r_i/r_o)^{\delta-1}}{r_o[1-(r_i/r_o)^{\delta}]} \quad (15)$$

Relationships (2), (15) yield straightforwardly:

$$E_{r,DC} = E_r = E_{r,i}\frac{r^{\delta-1}}{r_0^{\delta-1}}\frac{r_0^{\delta-1}}{r_i} = E_{r,i}\left(\frac{r_i}{r}\right)^{1-\delta} \quad (16)$$

that replaced into (11) provides:

$$F_N = 1-\exp\left\{-\frac{2\pi l}{V_l}\left(\frac{E_{r,i}}{\alpha_l}\right)^{\beta}\int_{r_i}^{r_o}\left[\left(\frac{r_i}{r}\right)^{\eta}\right] r dr\right\} \quad (17)$$

having defined

$$\eta = (1-\delta)\beta \quad (18)$$

Note that η is not a trivial quantity. Indeed, it depends on δ, that in turn (see (3)) depends on: inner and outer radius of the insulation, applied DC voltage, material characteristics (i.e. a, b, $\lambda_{T,d}$) and conductor losses W_C. (17) can be rewritten as:

$$F = 1-\exp\left\{-\frac{2\pi l}{V_l}\left(\frac{E_{r,i}}{\alpha_l}\right)^{\beta} r_i^{\eta}\int_{r_i}^{r_o} r^{1-\eta} dr\right\} \quad (19)$$

Integration of (19) between r_i and r_0 provides:

$$F = 1-\exp\left\{-\frac{2\pi l}{(2-\eta)V_l}\left(\frac{E_{r,i}}{\alpha_l}\right)^{\beta} r_i^2\left[\left(\frac{r_o}{r_i}\right)^{2-\eta} - 1\right]\right\} \quad (20)$$

By defining the following quantity $n(\eta)$, function of η

$$n_e(\eta) = \frac{2\pi l r_i^2}{(2-\eta)V_l}\left[\left(\frac{r_o}{r_i}\right)^{2-\eta} - 1\right] \quad (21)$$

that holds for $\eta \neq 2$, (20) can be recast in a more compact form:

$$F = 1-\exp\left\{-n_e\left(\frac{E_{r,i}}{\alpha_l}\right)^{\beta}\right\} = 1-\exp\left\{-\left(\frac{E_{r,i}}{\alpha_n}\right)^{\beta}\right\} \quad (22)$$

α_n being the 63.2th dielectric strength percentile on conductor:

$$\alpha_n = \alpha_l/[n_e(\eta)]^{1/\beta} \Leftrightarrow \alpha_l = \alpha_n[n_e(\eta)]^{1/\beta} \quad (23)$$

Relationship (23) is valid for any DC cable having the geometry of Fig. 1. Hence it can be written, in particular:

1. for a "small DC cable 1", featuring a relevant value $n_1(\eta_1)$ of n_e according to (21) based on length $l=L_1$, inner and outer insulation layer radii r_{i1} and r_{o1}, as well as on η_1, that is the value of η characteristic of cable 1;
2. for a "large DC cable 2", featuring a relevant value $n_2(\eta_2)$ of n_e according to (21) based on length $l=L_2$, inner and outer insulation layer radii r_{i2} and r_{o2}, as well as on η_2, that is the value of η characteristic of cable 2.

Indeed, both the "small" and the "large" cable are characterized by the same value of α_l relevant to the generic differential volume element $2\pi lrdr$. Therefore, since β is unchanged in the enlargement process due to the radial distribution of field strength along cable length [7,8,11], it holds:

$$\alpha_l = \alpha_1[n_1(\eta_1)]^{1/\beta} = \alpha_2[n_2(\eta_2)]^{1/\beta} \quad (24)$$

Hence, the ratio between the 63.2% dielectric strength α_1 of the "small" HVDC cable and the 63.2% dielectric strength α_2 of the "large" HVDC cable gives rise to the innovative enlargement law for HVDC cables, namely:

$$\frac{\alpha_1}{\alpha_2} = \left(\frac{L_2}{L_1}\right)^{1/\beta}\left(\frac{r_{i2}}{r_{i1}}\right)^{2/\beta}\left[\frac{(r_{o2}/r_{i2})^{2-\eta_2} - 1}{(r_{o1}/r_{i1})^{2-\eta_1} - 1}\right]^{1/\beta} \quad (25)$$

In which is valid for both η_1 and η_2 larger than 2 or for both η_1 and η_2 smaller than 2 [12].
Equation (25) can be recast in a more compact form, i.e.:

$$\frac{\alpha_1}{\alpha_2}=\left(\frac{L_2}{L_1}\right)^{\frac{1}{\beta}}\left(\frac{r_{i2}}{r_{i1}}\right)^{\frac{2}{\beta}}\times$$
$$\times \mathrm{H}_{DC}(r_{i1},r_{i2},r_{o1},r_{o2},V_{DC,1},V_{DC,2},W_{C1},W_{C2},\beta,a,b,\lambda_{Td})$$
(26)

where

$$\mathrm{H}_{DC}(r_{i1},r_{i2},r_{o1},r_{o2},V_{DC,1},V_{DC,2},W_{C1},W_{C2},\beta,a,b,\lambda_{Td})=$$
$$=\left[\frac{(r_{o2}/r_{i2})^{2-\eta_2}-1}{(r_{o1}/r_{i1})^{2-\eta_1}-1}\right]^{1/\beta}$$
(27)

where η_j (j being either 1 or 2) is given by:

$$\eta_j=(1-\delta_j)\beta \quad (28)$$

$$\delta_j=\left[\frac{aW_{Cj}}{2\pi\lambda_{T,d}}+\frac{bV_{DCj}}{(r_{oj}-r_{ij})}\right]\Big/\left[\frac{bV_{DCj}}{(r_{oj}-r_{ij})}+1\right] \quad (29)$$

Since in the DC case the maximum electric field in the insulation wall depends on the load, the 63.2th percentile of dielectric strength on the conductor is not so interesting as in the AC case. Consequently the 63.2th percentile of breakdown voltage (V_1 for the cable in the reduced state, V_2 for the cable in the enlarged state) is of much greater significance and the following relationship should be considered instead of (26):

$$\frac{V_1}{V_2}=\frac{\alpha_1}{\alpha_2}\cdot\frac{k_2}{k_1}\cdot\frac{\delta_2}{\delta_1} \quad (30)$$

where k_j (j being either 1 or 2) is given by:

$$k_j=(r_{ij}/r_{oj})^{\delta_j-1}/\{r_{oj}[1-(r_{ij}/r_{oj})^{\delta_j}]\} \quad (31)$$

APPLICATION OF THE LAW FOR HVDC CABLES

As an application of the novel enlargement law for HVDC cables, let us consider two extruded HVDC cables manufactured with the same insulation compound and characterized by the main geometrical and material parameters listed in Table I. The cables are a 200 kV full-size cable and a 300 kV full-size cable with the same cross-section, but the former is considered here as the "small" cable and the latter as the "large" cable: indeed, the aim of this example is to evaluate the 63.2% breakdown voltage of the 300 kV cable, V_2, as a function of cable length, L_2, starting from the knowledge of the 63.2% breakdown voltage of a length L_1=10 m of the 200 kV cable, V_1, at both 25 ℃ (unloaded cable) and 70 ℃. The analysis is performed resorting to relationship (30); the relevant values of the ratio V_2/V_1 vs. L_2 at the two

Table I. Main characteristics of the considered cables

Parameter	dimensions	200 kV cable	300 kV cable
Conductor cross section	mm^2	1400	1400
r_i	mm	22	22
r_o	mm	34	42
a (after [2])	$℃^{-1}$	0.084	0.084
b (after [2])	mm/kV	0.0645	0.0645
$\lambda_{T,d}$	$W\ m^{-1}K^{-1}$	0.286	0.286

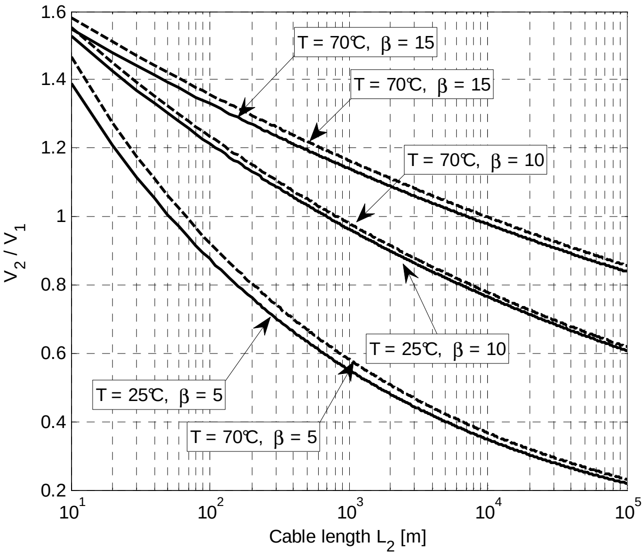

Fig. 2. V_2/V_1 vs. L_2 for different β values at 25 ℃ and 70℃.

service temperatures of 25 ℃ and 70 ℃ considering three typical values of the shape parameter β (5, 10 and 15) are reported in Fig. 2. The 300 kV cable is assumed directly buried within a uniform soil, having thermal resistivity of 1.3 K·m/W. Cable losses at 25 ℃ and 70 ℃ have been evaluated through [20,21].

As Fig. 2 shows, the ratio V_2/V_1 is >1 when L_2=L_1, thanks to the larger insulation thickness of the 300 kV cable, but a sharp decrease of the ratio as a function of "large" cable length L_2 is exhibited thereafter. The fastest decrease occurs for the lowest value of β, the slowest for the highest (as expected since a lower β means higher inhomogeneity of the compound, hence higher number of weak points over a given volume of insulation): at 25℃ V_2/V_1 equals unity for L_2=50 m when β=5, for L_2≈7.2 km when β=15, then it goes well below 1 reaching a limit value – for the highest length considered, 100 km – that is slightly higher than 0.2 when β=5, slightly higher than 0.8 when β=15. This means that, for long HVDC cable lines, a strong decrease of breakdown voltage occurs with respect to test lengths typically used, say, in type tests. Hence extrapolation of design and test values of breakdown voltages to the full length of the cable line should be regarded with care.

Similar observations hold at 70℃, although a quicker decrease of breakdown voltage of the large cable with cable length is obtained for the loaded cable. However, the effect of temperature does not seem of primary significance: indeed, the ratio [V_2/V_1(70°C)]/[V_2/V_1(25°C)] ranges from 1.05 (β=5) to 1.02 (β=15) when L_2=L_1=10 m, maintaining the same value when L_2=100 km.

Anyway, all these observations hold for the considered example. They should be checked on more case-studies on broader intervals of the parameters analyzed, as well as by examining the effects of other quantities not treated here, i.e. inner and outer insulation radii, electrical resistivity, heat dissipated through the cable layers and thermal resistivity of the insulation.

CONCLUSIONS

The paper shows how a reliability evaluation can be inferred starting from a life model and taking to account the enlargement law for extruded cables. The enlargement law that takes into account the effect radial and length on breakdown performance of a cable highlights its important role in the overall evaluation of cable reliability, this is particularly true for long cables as the case of HVDC cables.

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