HVDC aging modelling for polymeric cable: an overview

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ABSTRACT

This work presents an overview of the impact of HVDC electrical stress on insulation aging. In particular modelling is presented that provide life estimation of polymeric insulation subjected to dc stress on the basis of space charge measurements and short-term life tests realized at constant dc stress and under polarity inversions. The modelling is applied to results of life tests performed on polyethylene materials, in the perspective of providing guidelines for the design of polymeric-insulated dc cables. Finally, a few remarks on aging modelling under non-sinusoidal condition are also presented.

KEYWORDS

Cable insulation, space charge, polarity inversions, non-sinusoidal voltage.

INTRODUCTION

In the era of smartgrids and renewables, a wide potential market could be open to polymer-insulated dc cables in place of traditional oil-impregnated cables, once the problems associated with their reliability have been completely solved. Indeed, polymeric insulation commonly used for ac cables, i.e. cross-linked polyethylene (XLPE), may not endure dc stress due to, mainly, space charge accumulation in the insulation bulk and voltage polarity inversions, that are likely to occur in dc lines for energy-flow dispatching [1]. These issues have pushed several researchers towards the study of new polymeric materials, mostly obtained from PE or XLPE with appropriate additives or fillers, with the main aim of reducing the amount of charge stored at the design field of 20-30 kV/mm [2].

The characterization of the performance of these materials under dc voltage is generally achieved resorting to space charge measurements, but materials are generally evaluated based on the rule of thumb '*the lower the accumulated charge, the better the insulation performance'*. Even if it is generally accepted the significant role played by space charge on insulation performance, the analytical relationship between space-charge associated quantities and insulation endurance / life under electrical stress has not been thoroughly investigated.

A clear correlation between stored space charge, maximum internal field, rate of space charge depletion and ratio between life with and without polarity inversions is shown in [3], while a phenomenological approach to life modelling under dc stress is presented in [4]. Other works deal with physical modelling of insulation aging caused by electromechanical energy storage associated with space charge trapping [5].These approaches are based on short-time testing which is generally required when several candidate materials for an application have to be investigated. Even though applications usually impose requisites of long and reliable life, there is a lack of knowledge about the relation between short-term tests and long-term performance.

Besides space charge, big concerns are raised about insulation reliability of components connected with AC/DC and DC/AC power converters of HVDC links, like e.g. ac cables and power transformers (see Fig.1). Converters, in fact, generate very often non-sinusoidal voltage waveforms providing, e.g. dc components and/or several harmonics which can affect the network apparatus closer to the HVDC converters, e.g. ac-cable connections and power transformers.

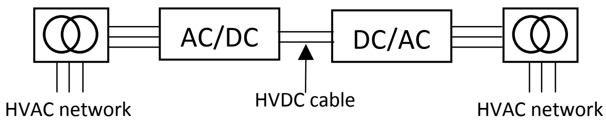

Fig. 1: Scheme of a network with an HVDC link

Conventional life models used to design insulation systems under ac conditions must be modified in order to account for space charge accumulation effect on dc-side and for possible harmonic pollution on ac-side of HVDC links. Next sections will deepen these topics.

THE ROLE OF SPACE CHARGE

It is generally accepted that the accumulation of space charge can constitute an important cause of insulation degradation. Several results show the existence of a relationship between space charge accumulation in polymeric insulation and dc aging. In particular, it has been observed that:

- an increasing amount of space charge tends to accumulate in the insulation with aging time;
- voltage polarity inversions accelerate dc insulation degradation, causing shorter life compared with aging under constant polarity dc electrical stress.
- large space charge accumulation accelerates degradation and shorten insulation breakdown time.

Polymer-insulated cables suffer from these problems, since space charge can be stored at design fields. In the case of XLPE, for example, heterocharge can form close to the electrodes even at quite low fields, e.g. 10 kV/mm [6, 7]. In addition, carriers injected from the electrodes can play a more significant role as the field increases, so that heterocharge can turn eventually into homocharge [8]. Both homocharge and heterocharge can affect cable reliability through local field amplification, electromechanical energy storage and also hot electron formation [9].

Heterocharge formation can be a serious concern for cable manufacturers since it can cause electric field amplification close to the electrodes exceeding the design field, which can eventually reduce insulation life. Moreover, as the design filed increases, space charge injection from the electrodes becomes larger, particularly at high temperatures, thus significant amount of space charge can accumulate in the insulation bulk. Figure 2 shows the space charge density accumulated in a specimen of XLPE cable insulation as a function of the maximum laplacian electric field (i.e., the field on the cable core surface) and temperature. The threshold field above which space charge is accumulated decreases from 11 to 3 kV/mm as temperature rises from 20 ℃ t o 70 ℃. It must be emphasized that the threshold for sp ace charge accumulation corresponds to that relevant to the transition of conduction mechanism from ohmic to space charge limited current (SCLC) [10]. It can be concluded that above the threshold for SCLC conduction, excess charge injection becomes a fundamental phenomenon.

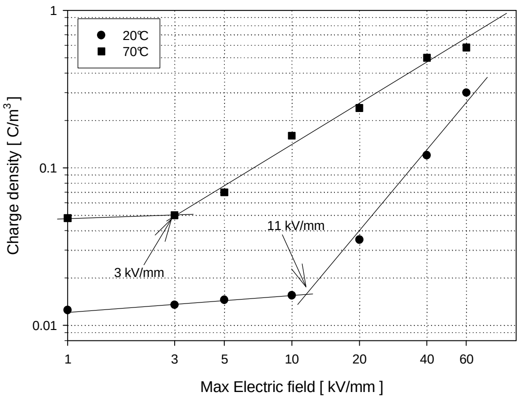

Fig. 2: Space charge buildup as a function of poling (laplacian) field for XLPE cable at 20℃ and 70 ℃.

In HVDC insulation heterocharge buildup close to one electrode is caused most likely by the injection of charge carriers from the opposite electrode. Indeed, injected charges trapped in relatively shallow traps can travel across the insulation, even though in quite long times, and may accumulate close to the counter electrode due to the semicon-insulation interface, which can provide a partially blocking effect to space charge extraction [11]. The semicon-insulation interface, in fact, plays an important role affecting both charge injection and extraction barriers [11, 12]. Alternatively, injected charge blocked in deeper traps close to the electrode as homocharge, can become heterocharge in case of voltage polarity inversions.

As previously mentioned, quite a few results of life tests performed on PE-based materials show that voltage inversion can shorten life significantly [13]. Figure 3 reports, as an example, the life lines obtained for XLPE specimens through life tests performed with and without voltage inversions at room temperature. Life (the breakdown time at probability 63.2% in the figure), is significantly shortened under voltage inversions, giving rise to life reduction of more than one order of magnitude. This phenomenon, which generates concerns for the installation of polymeric dc transmission cables where polarity inversions are expected, is claimed to be caused by the effect of space charge, which modifies (increases) the internal field after each inversion. This could be due, for example, to homocharges close to the electrodes, which turn into heterocharges when the field polarity is reversed. Field alteration is maintained for times much larger than in the case of oil-paper cables, due to the smaller mobility of charges in polymeric insulation.

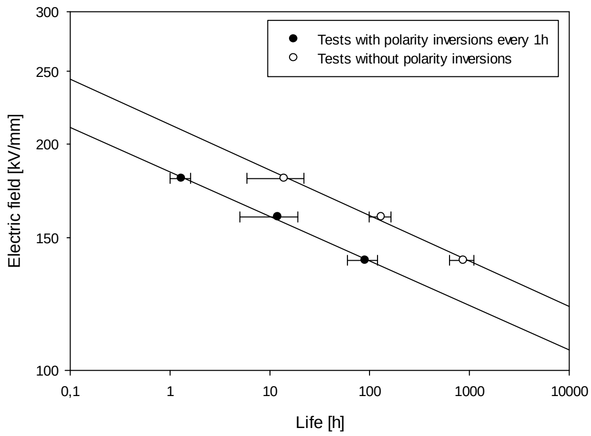

Fig. 3: Results of life tests with and without polarity inversions on XLPE flat specimens at 20 ℃.

Another striking evidence of the correlation between the extent of accumulated space charge and insulation life is reported in [1]. It shows that an XLPE specimen containing large part of its cross-linking by-products experiences breakdown after about 170 h at a nominal field of 10 kV/mm, that is, an extremely short life at a very low field. This surprising result can be explained by space charge measurements, which highlighted cathode field increase of 8 times with respect to the design value, i.e. actual fields of about 80 kV/mm, well able to accelerate degradation.

In conclusion, proofs of the influence of space charge on the dc degradation process are evident. We need, therefore, to extract from space charge measurements appropriate quantities correlated with insulation aging to be used for life modelling.

SPACE CHARGE PARAMETERS

The first parameter that could be calculated from space charge measurements is the maximum field, E_M, over the whole poling time. An example is provided in Fig. 4. It is noteworthy that the max value of E_M, which occurs just after voltage polarity inversion, is 230 kV/mm, that is 53% larger than the poling field (150 kV/mm).

Another quantity which can be evaluated from space charge measurements is the maximum stored charge density, Q_M, calculated as the integral of the charge density profile, usually at the end of the polarization period, see [3].

The behaviour of Q_M as a function of applied electric field is called 'space charge threshold characteristic' as shown in Fig. 2. Another example is reported in Fig. 5 (E_T is the threshold field). Since the plot is in log-log coordinates, the relationship between Q_M and E is a power law [3]:

$$Q_M = CE^b \qquad (1)$$

where b is the slope of the space charge characteristic.

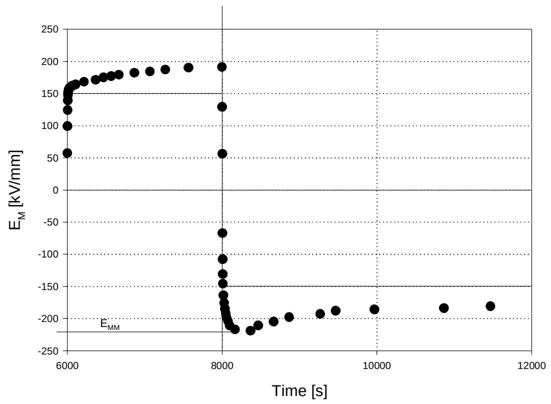

Fig. 4: Threshold characteristics for XLPE cable at 20°C and 70 °C

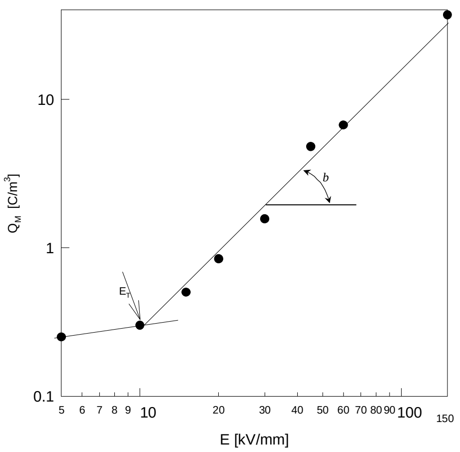

Fig. 5: Example of space charge threshold characteristics. The threshold field E_T is indicated by the arrow

Another important parameter which can be derived from space charge measurements is the slope of depolarization characteristic, *s*, which accounts for the speed of charge extraction from traps [3]. Indeed, it can be argued that the larger the slope (i.e. the faster charge depletion), the smaller the effect of polarity inversion on life.

LIFE MODELLING

A very simple life model expressing insulation life under electrical stress is provided by the well-known Inverse Power Model (IPM), which can be written as:

$$L = L_H \left(\frac{E}{E_H} \right)^{-n} \qquad (2)$$

where *E* is the rms of the field providing life *L*, E_H is the rms of a reference field, L_H is the relevant life and *n* is the Voltage Endurance Coefficient (VEC).

This model is still valid also under dc supply with E = laplacian field, if no space charge accumulates in the insulation. Otherwise, the laplacian field E should be substituted by the actual (poissonian) field inside the insulation, which can be distorted (e.g. enhanced) by space charge build-up. It can be understood that it is very difficult to evaluate *a priori* the actual field, thus equation (2) cannot be used straightforwardly to design insulation in the presence of space charge accumulation. However, equation (2) can help to evaluate approximately the life reduction corresponding to the increase of electric field at insulation-conductor interface due to heterocharge accumulation. As an example, Fig. 6 shows the plot of eq. (2) for an XLPE insulation having n=15 and life of 30 years at the design field of 30 kV/mm. It can be noted that a small increment of the electric field of 10% is able to reduce the life of about 5 times.

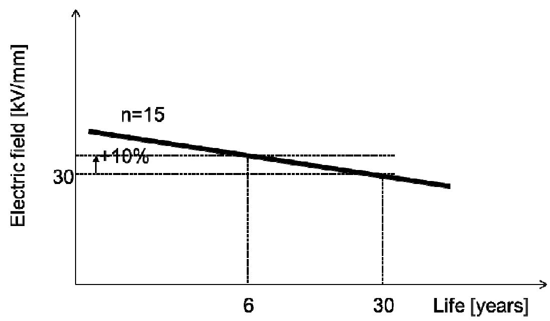

Fig. 6: Lifeline of eq. (3) with slope n=15. The life reduction for a field increase of 10% is indicated.

Life modelling under dc with polarity inversions

In the presence of voltage polarity inversions, equation (2) is not appropriate to model insulation life. In this case, polarity repetition frequency has to be taken into account because polarity reversals enhance the effect of space charge accumulation. A simple, but effective model, has been described in [14] accounting for life with polarity inversions, L_i, in relative value to the life without inversions, *L*, that is:

$$\ln[(L/L_i) - 1] = b \ln(KE) + A \ln(f) \qquad (3)$$

where K is a coefficient function on the slope, *s*, of the space charge depolarization characteristic and *A* is associated with the dependence on *f*, the polarity inversion frequency [14].

The determination of the parameters of model (3) can be carried out through linear regression applied to the life test experimental data in log-log plot together with the calculation of the quantities obtained from space charge measurements as previously explained.

Substituting the general eq. (2) into eq. (3), the following model is provided [14]:

$$L_i = \frac{L_H \left(\frac{E}{E_H} \right)^{-n}}{1 + KE^b f^A} \quad (4)$$

that gives an estimate of life of insulation with voltage inversion at any field and inversion frequency, including *f*=0, i.e dc voltage without inversions. Indeed, in this case equation (4) correctly reduces to eq. (2), since by definition $L_i(f=0)=L$.

An example of good fitting of eq. (3) to experimental life test data obtained under dc supply with and without polarity inversions on XLPE flat specimens is shown in Fig. 7.

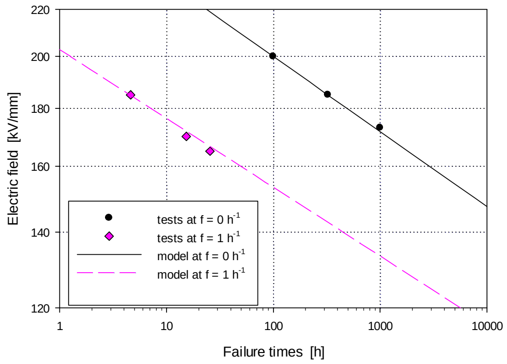

Fig. 7: Experimental test data and fitting model for life tests with and without polarity inversions on XLPE flat specimens at 20°C.

Life modelling under harmonic-voltage supply

As mentioned in the Introduction, power converters used in HVDC distort the voltage on the ac-side, affecting particularly the converter transformers (see Fig. 1). The extent of voltage distortion depends on the type of converter and switching modulation technique used. In particular, a dc component, voltage surges and notches can be present in the voltage waveforms [15, 16]

Again, simple life models like that of eq. (2) are not appropriate in this case. Under non-sinusoidal conditions, in fact, there are more factors characterizing voltage waveform, e.g. peak, slope and rms, which can be correlated to aging [17]:

$$K_P = \frac{E_P}{E_{1P}^*} \quad (5)$$

$$K_{rms} = \frac{E_{rms}}{E_{1rms}^*} \quad (6)$$

$$K_f = \left. \frac{dE(t)}{dt} \right|_{rms} \quad (7)$$

where E_1^* is the reference field, E_P and E_{rms} are peak and rms values of the considered waveform

In case the voltage waveform could be expressed by Fourier series, factor K_f becomes [17]:

$$K_f = \frac{\omega_1}{\omega_0} \sqrt{\sum_{h=1}^{N} h^2 \alpha_h^2} \quad (8)$$

were *N* is the amount of harmonic components of noticeable amplitude contained in the voltage waveform, ω_1 is the angular frequency of the fundamental component, ω_0 = 314 rad s^{-1} is the angular frequency of the reference 50 Hz sinusoid, *h* is the harmonic order, $\alpha_h=V_h/V_1$.

If the voltage waveforms are provided by pulse width modulation, eq. (7) takes the following expression [18]:

$$K_f = \lambda \frac{\sqrt{f/t_r}}{\omega_0} \quad (9)$$

where *f* is the switching frequency, t_r the rise time of the considered waveform (here equal to the fall time); ω_0 = 314 rad/s; λ = 2 or 2·√2 for unipolar or bipolar waveforms, respectively.

A multifactor life model can be obtained generalizing the IPM model of eq. (2), that is:

$$L = L_0 K_f^{-a} K_p^{-b} K_{rms}^{-c} \quad (10)$$

where L_0, *a*, *b* and *c* are the model parameters which can be estimated through multi-variable linear regression of life test data.

CONCLUSIONS

Life modelling of insulation systems under HVDC supply must account for space charge, which is able to enhance the internal electric field, affecting thus insulation reliability. In particular, attention should be paid to the presence of heterocharge in HVDC cables supplied by VSC converters (no voltage polarity change are expected), which can magnify the electrode field. In case of LCC converters space charge accumulation in insulation systems exhibit the most detrimental effect at voltage polarity inversions. If the polarity repetition rate is not known accurately, a probabilistic approach could be the most appropriate procedure to apply. Moreover, non-sinusoidal voltage waveforms generated by power converters can affect insulation reliability in the ac-network and should be considered for proper life modelling.

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