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The Effects of Seasonal Factors on Life and Reliability of High Voltage ac Cables subjected to Load Cycles

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Abstract--In previous articles by this author, a procedure was set up and validated for life and reliability evaluation of HV cables subjected to the time-varying electro-thermal stress associated with the typical daily cycles of conductor current. In this paper, the procedure is improved to account for the effects of seasonal factors, by taking for every season different daily cycles of cable current, as well as different values of thermal resistivity and temperature of the soil. The procedure is applied to a case-study HVAC XLPE-insulated cable. The results show that the fraction of life and reliability lost by cable insulation is strongly dependent on seasonal factors, in particular on soil resistivity and temperature, and the vast majority of cable life and reliability is lost within the hot (summer) season.

Index Terms--Cross linked polyethylene insulation, Failure analysis, Life estimation, Power cables, Power distribution reliability, Reliability estimation.

I. INTRODUCTION

THE concern for the environmental impact of overhead lines and the quest for higher reliability and availability of power delivery place HV cables under the spotlight as the favorite tool for developing transmission and distribution grids, especially in Europe. Thus, a sound life expectancy evaluation of HVAC cables on duty is appealing, since it helps TSOs and DSOs in planning new cable lines and – along with accurate condition-monitoring – in optimizing maintenance actions and life extension procedures of existing cable lines.

HV cables are designed taking service stresses on cable insulation as steadily equal to rated stresses - first and foremost maximum temperature, linked to current, and maximum electric field, linked to voltage. This makes life and reliability evaluation of HV cables on duty not trivial. Indeed, typically:

- 1) cable current and maximum insulation temperature vary with time according to daily load cycles and are mostly well below their rated values. Therefore, cables tend to live longer than design life [1]-[3], but this cannot be

accounted for by IEC Standard 60853 [4],[5], which does not provide cable life estimates under load cycles;

- 2) seasonal factors strongly affect the physical state of the soil where HV cables are laid, especially its temperature and humidity, thus thermal resistivity. In turn this affects the heat exchange between the cable and the soil.

In this respect, many literature papers (e.g. [6]-[11]) explain the sharp increase of cable system failure rates under heat waves experienced by utilities - even at moderate load levels - with the acceleration of insulation aging because of the worse heat dissipation caused by adverse conditions of the environment: high temperature and no rainfall. In particular in [7] it is pointed out that utilities experience higher failure rates where cable lines undergo strong temperature variations over the seasons – e.g. 40°C in summer vs. below 0°C in winter – with most failures taking place in summer and autumn. Furthermore, in [11] it is observed that recently an increase is observed in the failure rate of underground power cables in correlation with seasonal periods of extreme drought and temperatures; as a consequence underground cables, at a given load, are overheated with unavoidable accelerated aging of both the cables and the joints, until in some cases insulation failure occurs. Therefore, an accurate estimation of the expected life of new HV cables – or of the remaining life of existing HV cables – requires proper consideration not only of the effects of the time varying electro-thermal stress associated with load cycles, but also of seasonal factors, which affect the energy demand and thus the cable load, too.

In previous articles by this author, a procedure was set up and validated for life and reliability evaluation of HV cables subjected to the time-varying electro-thermal stress due to load cycles [1],[2],[12],[13]. The procedure, developed for HVAC cables first [1],[2] and DC cables later [12],[13], is capable of modeling the thermal transients of cable layers caused by the typical daily cycles of conductor current and of estimating the relevant insulation aging cumulated throughout cable life. This procedure was also used, e.g. in [3], to forecast the residual life of cables on duty via a sound analysis of load conditions experienced in the past and a reasonable extrapolation of load conditions to the future.

However, so far the procedure has considered only average daily cycles over the year, without accounting for the seasonal

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variation of the load, as well as for seasonal (climatic and meteorological) changes of the temperature and thermal resistivity of the soil. In this respect, the goal of this paper is twofold.

- 1) Proposing an improved estimation procedure of life and reliability of HVAC cables subjected to load cycles in the presence of seasonal values of the load current and of the physical parameters of the soil that affect heat exchange (temperature and thermal resistivity).
- 2) Investigating, via the improved procedure, possible criticalities that might arise if seasonal factors are not properly taken into account in cable design. Such criticalities [7] – perhaps not sufficiently addressed so far, especially in mild climates – are now more challenging due to global warming [11].

In Section II of this paper, the previous procedure is recalled and in Section III the improved procedure is described. In Section IV, the improved procedure is applied to a typical HVAC XLPE-insulated cable by considering for every season different daily cycles of cable current derived from monitored data of load demand in the Italian network, different values of the temperature of the ground derived from monitored data of soil temperature and different values of the thermal resistivity of the soil derived from literature studies on the humidity of the soil. The results show that the fraction of life and reliability lost by cable insulation is strongly dependent on seasonal factors, in particular on temperature and resistivity of the soil. Conclusions and future perspectives of this investigation are reported in Section V.

It should be pointed out that for the sake of simplicity the procedure neglects at present some aging effects occurring in real HVAC cables, e.g. thermo-mechanical cycles and electrical overstresses due to voltage surges. However, in the future these and other aging effects might be included in the procedure by following a similar cumulative approach.

II. CABLE LIFE ESTIMATION UNDER LOAD CYCLES

The procedure set up and validated previously for life and reliability evaluation of HV cables subjected to load cycles [1],[2],[12],[13] is based on some meaningful hypotheses for the typical service of power cables. Focusing here on HVAC cables, such hypotheses are the following.

- 1) Relying on the probabilistic approach to power system component design [1],[2],[12]-[14], it is assumed that cable life coincides with the time to the attainment of a given failure probability, P , or – more briefly – that cable life is the time-to-failure at failure probability P .
- 2) The times-to-failure t_F of HVAC cables follow the Weibull cumulative probability distribution function (cdf) commonly used for extruded power cables, i.e.:

$$P(t_F) = 1 - \exp[-(t_F / \alpha_t)^{\beta_t}] \quad (1)$$

where α_t (63.2th failure-time percentile), is the scale

parameter of the cdf and depends on applied stresses; β_t is the shape parameter of the cdf¹ [1],[2],[12]-[14].

- 3) Among the models for estimating cable life at constant temperature T and electric field E [3],[15]-[19], the so-called IPM-Arrhenius life model is used. As shown in [1],[2],[12],[15], it merges the phenomenological IPM life model (the reference electrical life model of IEC Standard 62067) and the physical Arrhenius life model (the reference thermal life model of IEC Standard 60216); moreover it fits well accelerated life test results relevant to XLPE-insulated cable models [20]. The IPM-Arrhenius life model can be written as [12]:

$$L[E,T] = L_D [E/E_D]^{-(n_D - b_{ET} T')} [E_D/E_0]^{b_{ET} T'} e^{-BT'} \quad (2)$$

where: L_D is the design value of cable life (at design failure probability P_D); E_D and T_D are respectively the design values of maximum electric field and temperature in the insulation; $n_D = n_0 - b_{ET}(1/T_0 - 1/T_D)$, n_0 being the life exponent at reference temperature T_0 ; $T' = 1/T_D - 1/T$ is thermal stress; $B = \Delta W/k_B$, ΔW being the activation energy of the main degradation reaction of the insulation and k_B Boltzmann's constant; b_{ET} is a positive quantity ruling the synergism between electrical and thermal stress; E_0 is the field value below which electrical aging is negligible [12],[15].

- 4) Rms cable current on duty follows “stepwise-constant” daily cycles lasting for $t_d=1$ day and consisting of $N=24$ hourly steps². Each step has height I_j (rms current value in the j^{th} step) and duration $\Delta t_j=1\text{h}$ ($j=1,\dots,N=24$). The procedure can work, of course, even with $N>24$ at the price of longer computing time, but 24-hour load cycles can reproduce the average yearly operation of most HVAC cable systems worldwide [4] and are applied during the qualification tests of HVAC cables according to IEC Standards 60840 and 62067 [21],[22].
- 5) The weakest part of the cable is its insulation.
- 6) The electrical stress due to AC voltage and the thermal stress due to temperature are the main stresses acting on cable insulation in service [15].
- 7) Electrical and thermal stresses interact with each other, leading to the so-called electro-thermal synergism [15].
- 8) Maximum electric field and temperature in cable insulation occur at conductor-insulation interface, i.e. at radial coordinate $r=r_i$ (inner insulation radius). There, electro-thermal aging is the strongest and insulation fails due to the aging cumulated over service life.
- 9) Maximum electric field $E(r_i)$ is constant with time, since the voltage applied to cable insulation is constant and equal to rated phase-to-ground voltage.

¹ The possible dependence of β_t on applied stresses is much weaker [12],[14].

² Typically cables see different load on weekdays vs. weekend days. This aspect - skipped here both for the sake of brevity and because focus is on seasonal effects rather than on weekly changes - will be treated in the future via the same cumulative approach, involving more complex implementation.

10) Maximum temperature $T(r_i, t)$ varies with time due to the daily load cycles of cable current.

From these hypotheses, the procedure for estimating life L of AC cables under load cycles is split in the following steps.

I) Calculation of the transient temperature $T(r_i, t)$ at conductor-insulation interface for every time t of daily cycles via the thermal analog of transient Ohm's law, which represents cable and soil layers as a ladder network of series thermal resistances (simulating heat conduction through the layers) and shunt thermal capacitances (simulating heat storage within the layers). Details can be found in [1]-[3],[4],[9].

II) Calculation of the life fraction dLF lost by cable insulation in each infinitesimal interval dt between t and $t+dt$. Since $dt \rightarrow 0$, $T(r_i, t)$ can be deemed constant between t and $t+dt$. Then, dLF is computed as follows:

$$dLF = dLF[E(r_i), T(r_i, t)] = dt / L[E(r_i), T(r_i, t)] \quad (3)$$

where $L[E(r_i), T(r_i, t)]$ is life at constant temperature $T(r_i, t)$ – known from previous point I) - and constant AC field $E(r_i)$. $L[E(r_i), T(r_i, t)]$ in (3) is estimated via (2) at constant temperature $T(r_i, t)$ and electric field $E(r_i)$.

III) Application of Miner's law [23], by setting the sum (in fact an integral) of all fractions of life lost dLF equal to 1 at failure, thereby obtaining from (3):

$$\int_0^L dLF = \int_0^L dt / L[E(r_i), T(r_i, t)] = 1 \quad (4)$$

IV) Solution of (4) in the unknown L , thereby attaining HVAC cable life under time-varying temperature.

It must be pointed out that, under hypothesis 4) above, relationship (4) can be recast as follows:

$$M \times \int_0^{t_d} dLF = M \times LF_d = M \times \sum_{j=1}^N LF_j = 1 \quad (5)$$

$$M = 1 / LF_d \quad (6)$$

$$LF_j = \int_0^{\Delta t_j} dLF = \int_0^{\Delta t_j} dt / L[E(r_i, t), T_j(r_i, t)] \quad (7)$$

where the following quantities have been introduced:

- i) M = number of daily “cycles-to-failure” of cable insulation. The calculation of M via (6) provides a straightforward estimation of cable life in days;
- ii) LF_d = fraction of life lost by cable insulation during each daily load cycle;
- iii) LF_j = fraction of life lost by cable insulation during the j^{th} step of each daily load cycle;
- iv) $T_j(r_i, t)$ = transient temperature at radius r_i within each j^{th} step Δt_j of the daily load cycle.

III. INCLUDING SEASONAL FACTORS IN THE PROCEDURE

In fact, as pointed out in Section I, seasonal factors affect strongly the heat exchange properties of the soil and the daily

load cycles themselves. Indeed, given a certain electrical load, generally HV cables warm up more in summer – particularly during heat waves – than in the other seasons, when ambient conditions are more favorable. This is shown by the well-known steady-state thermal Ohm's law, on which IEC Standard 60287 for cable ampacity calculation is based [24]:

$$T_c - T_a = R_{T,d}(W_c + P_d / 2) + R_{T,g}[W_c(1 + \lambda) + P_d] + R_{T,t}[W_c(1 + \lambda) + P_d] \quad (8)$$

whereby the heat flow due to conductor losses W_c , dielectric losses P_d and sheath losses λW_c through the thermal resistance of insulation, $R_{T,d}$, thermoplastic outersheath, $R_{T,g}$, and soil $R_{T,t}$, causes an increase in conductor temperature T_c with respect to the unperturbed temperature T_a of the soil.

Ohm's law (8) explains that the increase of conductor temperature T_c in summer is “threefold” [25], as in summer:

- 1) a higher value of T_a - because of higher outdoor temperature - involves a higher value of T_c in (8);
- 2) a higher value of T_a and low/no rainfalls imply a lower value of saturation degree, h , namely the fraction of empty spaces of the soil which are filled with water³. The thermal resistivity of the soil, $\rho_{T,b}$ decreases as h increases, according to the following formula [8]:

$$\rho_{T,t} = \rho_w^G \cdot \rho_0^{(1-G)} \cdot e^{[3.08 \cdot (1-h)^2 \cdot G]} \quad (9)$$

where: ρ_w = thermal resistivity of water = 1.7 K·m/W; ρ_0 = thermal resistivity of the solid phase of the soil in its dry state, G = porosity of the soil. From (9), a lower value of h in summer implies a higher value of $\rho_{T,t}$ and thermal resistance $R_{T,t}$ of the soil. As $R_{T,t}$ plays a major role in the heat transfer from underground cables to the soil [26], this implies a higher value of T_c in (8);

- 3) a higher value of T_c means higher electrical resistance of the conductor, which in turn leads to an increase of conductor losses W_c , further enhanced by the higher power demand of buildings because of air-conditioning [11]. This further increases T_c in (8).

Such conductor temperature increase in summer raises maximum insulation temperature, thereby accelerating the thermal aging of the insulation and the relevant synergism between electrical and thermal stress. This may eventually reduce the life and the reliability of HVAC cables.

To include seasonal factors in the procedure for life and reliability estimation of HVAC cables subjected to load cycles, let us assume for the sake of simplicity that the seasonal daily load cycles, as well as the seasonal values of temperature and thermal resistivity of the soil, can be well represented by seasonal average values. Then, HV cable life can be estimated by defining $LF_{j,k}$ ($j=1, \dots, N=24$; $k=1, \dots, K=4$) as as the fraction of life lost by cable insulation during the j^{th} step of each daily load cycle of the k^{th} season. Hence, $LF_{j,k}$ can

³ h is non-dimensional, ranges from 0 to 1 (or from 0% to 100%) and is also called soil relative humidity, being similar to the relative humidity of free air.

be calculated similarly to LF_j in (7), as follows:

$$LF_{j,k} = \int_0^{\Delta t_{j,k}} dt / L[E(r_i), T_{j,k}(r_i, t)] \quad (10)$$

where $T_{j,k}(r_i, t)$ denotes the transient temperature at radius r_i within each j^{th} step $\Delta t_{j,k}$ of the daily load cycle of every k^{th} season. $T_{j,k}(r_i, t)$ is calculated via the above-mentioned transient thermal model of the procedure on the basis of seasonal values of daily load current, soil temperature and thermal resistivity.

Examples of the shape of average daily load cycles for spring ($k=1$), summer ($k=2$), autumn ($k=3$) and winter ($k=4$) are plotted in Fig. 1, which shows power demand in Italy for typical Wednesdays (central days of the week) of the four seasons in 2018 - data downloaded from Terna's (the Italian TSO) website [27]. Of course, power demand in the ordinate of Fig. 1 has to be replaced by rms cable current for cable life estimation. Moreover, depending on the case of interest, more accurate seasonal averages of daily load cycles can be calculated from TSOs databases of load recorded in the past for a certain HV cable line, or guessed for the future service of an existing or a planned line according to the methods shown in [3]. In addition, seasonal averages can be even replaced by averages over shorter periods, at the price of setting $K > 4$ in (10), thus increasing computation time.

Examples of values of temperature and thermal resistivity of the soil that can be used as a reference for seasonal averages are reported in Clauses 4.2.1-4.2.3 and Annex 9 of IEC Standard 60287-3-1 [28]. However, these values single out the reference operating conditions of cables in order to calculate cable current rating. Since here focus is also on anomalous values of temperature and thermal resistivity of the soil as a worst-case condition - e.g. associated with heat waves - more accurate seasonal averages of temperature and thermal resistivity of the soil can be obtained from monitoring activities performed locally on cable lines [25].

The fraction of life lost in the k^{th} season, LFS_k , can be calculated from the various $LF_{j,k}$ obtained from (10), i.e.:

$$LFS_k = day_k \times \sum_{j=1}^{24} LF_{j,k} \quad (11)$$

where day_k is the number of days within the k^{th} season.

Therefore, the total fraction of life lost in one year of service of the HV cable, LFY , can be computed from the various LFS_k relevant to the four seasons ($k=1, \dots, 4$), as follows:

$$LFY = \sum_{k=1}^4 LFS_k = \sum_{k=1}^4 \left(day_k \times \sum_{j=1}^{24} LF_{j,k} \right) \quad (12)$$

Eventually, based on Miner's law [23], the relationship whereby HV cable life can be evaluated in the hypothesized seasonal service conditions is the following:

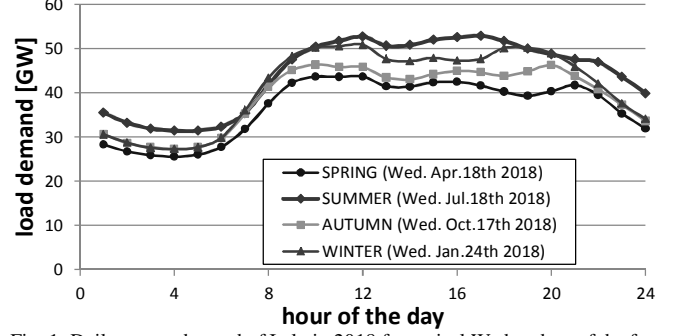


Fig. 1. Daily power demand of Italy in 2018 for typical Wednesdays of the four seasons (data downloaded from Terna's website [27])

$$L_y \times LFY = 1 \quad (13)$$

where life L_y is expressed in years. Therefore, from (13) L_y and M are obtained trivially as:

$$L_y = 1 / LFY \quad (14)$$

$$M = L_y \times 365 \quad (15)$$

since M is defined - see (5),(6) above - as the number of "daily cycles-to-failure" of cable insulation.

From (10)-(15) it stems that the improved procedure for life estimation of HVAC cables including average seasonal values for temperature and thermal resistivity of the soil, as well as for daily load cycles, can be summarized in the sequential calculation of the following quantities:

- the transient temperature profiles in every j^{th} step of each daily load cycle of each k^{th} season, $T_{j,k}(r_i, t)$ calculated via the above-cited transient thermal model;
- the life fractions lost in every j^{th} step of each daily load cycle of each k^{th} season, $LF_{j,k}$, by means of (10);
- the life fractions lost in every k^{th} season of one year of service, LFS_k ($k=1, \dots, 4$), by means of (11);
- the total life fraction lost in one year of service, LFY , by means of (12);
- the life in years, L_y , by means of (14), and/or the life in days, M , by means of (15).

Applying hypothesis 2) at Section II, cable reliability can be estimated from (10)-(15) by assuming that also life in the presence of seasonal values of load cycles and soil parameters - L_y in years, see (14), or M in days, see (15) - is Weibull-distributed according to (1), where now α_t is a function of seasonally-applied stresses. The design value of cable life L_D (of course in the absence of load cycles) in the constant-stress life model (2) used in this procedure is relevant to design failure probability P_D , hence it can be shown that L_y and M are also relevant to such failure probability [12]. Hence (1) can be written for $P=P_D$ and $t_f=L_y$ or M , as follows:

$$P_D = 1 - \exp[-(L_y / \alpha_t)^{\beta_t}] = 1 - \exp\{-(M / 365) / \alpha_t\}^{\beta_t} \quad (16)$$

From (16), α_t in the presence of seasonal variations of temperature and thermal resistivity of the soil, as well as of daily load cycles, can be estimated as follows:

$$\alpha_t = L_y / [-\ln(1 - P_D)]^{1/\beta_t} = (M/365) / [-\ln(1 - P_D)]^{1/\beta_t} \quad (17)$$

Then, by introducing (17) for α_t in (1) one can estimate the reliability at mission time t_F of HVAC cables subjected to seasonal values of load cycles and soil parameters, as follows:

$$R(t_F) = \exp\{-(t_F / L_y)^{\beta_t} [-\ln(1 - P_D)]\} \quad (18)$$

IV. CASE-STUDY: HVAC XLPE-INSULATED CABLE

A. HVAC Cable Selected for the Case-study

The improved procedure for life and reliability estimation of HVAC cables subjected to load cycles including the effects of seasonal factors, described at previous Section III, is applied here to a typical HVAC XLPE-insulated cable whose main design parameters are listed in Table I. The values of material properties for copper conductor, XLPE insulation and HDPE outer covering omitted in the Table for the sake of brevity are those listed in IEC 60287 and 60853 [4],[24],[26],[28]. This cable was already studied in [1],[2], but here the value of P_D is reduced and the value of L_D increased, to account for the improvements of cable design and technology.

It should be highlighted that cable ampacity (1015 A) is calculated according IEC 60287 in its various parts, i.e.:

- Part 1-1, as for full load ampacity equations [24];
- Part 2-1, as for the thermal resistance of the soil [26];
- Part 3-1 [28] as for temperature and thermal resistivity of the soil. In particular, as per Annex A.9 (relevant to Italy) the most conservative values are used of:
 - the unperturbed soil temperature, $\theta_a=20^\circ\text{C}$;
 - the thermal resistivity of the soil, $\rho_{T,t}=1.0 \text{ K m/W}$.

Since these are the standard values considered by cable manufacturers [1]-[3], choosing these values will enable to single out the role of possible adverse environment conditions which are not accounted for in routinary design procedures.

Model (2) is assumed to hold for the XLPE insulation, with the values of model parameters listed in Table II. These values were obtained from accelerated life test results relevant to XLPE-insulated cable models after [20], by extrapolating them to full-size HVAC cables [1],[2]. As for the electro-thermal stress synergism parameter b_{ET} , a sensitivity analysis is performed here like in [12] to study its role, by setting:

- 1) $b_{ET}=0 \text{ K}^{-1}$ as in [13], the value which can be shown to yield the maximum aging effect and life reduction with respect to design life for $T>T_D$ [15];
- 2) $b_{ET}=4420 \text{ K}^{-1}$ as in [1],[2], the experimental value derived for the XLPE cable models described in [20], which can be shown to yield a lower reduction of insulation life with respect to design life for $T>T_D$ [15].

As far as the shape parameter of the Weibull distribution is concerned, used for reliability estimation via (18), a value of $\beta_t=2$ was taken in [1],[2], which implies a failure rate linearly-increasing with time; this is usually the case of

TABLE I
MAIN DESIGN PARAMETERS OF THE TREATED CABLE

General design parameters of the cable	
rated rms line-to-line voltage [kV]	145
rated temperature, θ_D [$^\circ\text{C}$] ⁴	90
design life, L_D [y]	40
design failure probability, P_D [y]	0.01
ampacity [A]	1015
stranded copper conductor cross section [mm^2]	800
XLPE insulation thickness [mm]	17
insulation relative permittivity, ϵ_r [non-dimensional]	2.3
insulation loss factor, $\tan\delta$ [non-dimensional]	0.001
HDPE outer covering thickness [mm]	4
soil unperturbed temperature, θ_a [$^\circ\text{C}$]	20
soil thermal diffusivity, δ [$\text{m}^2 \text{ s}^{-1}$]	$0.5 \cdot 10^{-6}$
axial depth of burial of hottest cable, L_b [m]	1.5
horizontal cable spacing (plane cable-layout) [m]	0.25

TABLE II
VALUES OF MODEL (2) PARAMETERS FOR THE TREATED CABLE

E_D , design electric field at conductor/insulation interface [kV/mm]	7.2
B [K]	12430
b_{ET} (max. aging effect of synergism for $T>T_D$) [K] ⁵	0
b_{ET} (experimental, moderate aging effect of synergism for $T>T_D$) [K]	4420
n_D [non-dimensional]	15
E_0 [kV/mm]	6

TABLE III
SEASONAL AVERAGES OF SOIL THERMAL RESISTIVITY, $\rho_{T,t}$, CHOSEN FOR THE CASE-STUDY AND RELEVANT VALUES OF SATURATION DEGREE h FROM (9)

Season ↓	$\rho_{T,t}$ [K m/W]	h [%]		
		Sandy soil ($G=0.4$, $\rho_0=0.25 \text{ K m/W}$)	Silty soil ($G=0.5$, $\rho_0=0.5 \text{ K m/W}$)	Clay soil ($G=0.5$, $\rho_0=0.43 \text{ K m/W}$)
summer	1.3	53.3	88.2	85.3
autumn	1.0	70.5	97.3	94.8
spring	1.0	70.5	97.3	94.8
winter	0.85	79.3	100	100

severely-aged cable insulation and/or fairly high-load levels. Beside this value, in this case-study – where maximum load levels are lower than in [1],[2], see below – a value of $\beta_t=1$ is used, too, which involves constant failure rate with time; this usually occurs in the presence of the mild aging commonly associated with moderate load levels.

B. Choice of the Seasonal Factors

As for the effect of seasonal factors on soil temperature, monitoring activities close to buried cables [25] have shown that in urban areas of Southern Italy the unperturbed soil temperature is $\approx 30^\circ\text{C}$ and over in summer, $\approx 20^\circ\text{C}$ in spring and autumn, $\approx 15^\circ\text{C}$ in winter. Thus, the values taken as seasonal averages of θ_a in the case-study are as follows:

- $\theta_a(\text{summer})=30^\circ\text{C}$;
- $\theta_a(\text{spring})=\theta_a(\text{autumn})=20^\circ\text{C}$;
- $\theta_a(\text{winter})=15^\circ\text{C}$.

As for the thermal resistivity of the soil $\rho_{T,t}$, the following values have been taken as seasonal averages, based on the one hand on Clause 4.2.3 and Annex 9 of [28] and on the other hand on formula (9) applied to literature values of ρ_0 and G for typical sandy, silty and clay-type soil [8],[9]:

⁴ T indicates temperatures in K, θ indicates temperatures in [$^\circ\text{C}$]

⁵ The dimension of b_{ET} [K mm/kV] in previous papers [1],[2],[12] was wrong.

- 1.3 K m/W for summer, when the soil is on average warmer and drier than all other seasons;
- 1.0 K m/W (associated with “*moist*” soil condition and “*regular rainfalls*” weather condition according to [28]) for autumn and spring, when the soil is on average cooler and wetter than in summer;
- 0.85 K m/W (in between the former value and that associated with “*continuously moist*” weather condition and “*very moist*” soil according to [28]) for winter, when the soil is colder and wetter than all other seasons.

These seasonal averages of $\rho_{T,t}$ are compared in Table III to the corresponding values of saturation degree h obtained from (9) for sandy, silty and clay-type soil with typical values of porosity G [6]. Table III shows that not only these seasonal averages correspond to fairly different values of saturation degree h for different types of soil, but also these values of h are fairly high: hence, they are not granted, especially in summer, although the laying depth of HV cables is high (typically $\approx 1.3\text{-}1.5 \text{ m}$). Higher values of thermal resistivity of the soil in summer⁶ are discarded here, because selected backfills are often used, which grant fairly low values of $\rho_{T,t}$ even with h well below the values listed in Table III [3],[6].

To deal with the selected seasonal averages of daily load cycles, the shape chosen for the average 24-hour daily current in each season is the same as the shape of the corresponding 24-hour daily demand in Fig. 1. Indeed, the ratio “average hourly seasonal current” over “maximum current in the year” is equal to the ratio “hourly seasonal demand” over “maximum demand in the year” of Fig. 1. As for rms current magnitude, three values of mean load over the year, I_{ave} , have been chosen:

- 1) $I_{ave}=812 \text{ A}$, i.e. 80% of cable ampacity ($=1015 \text{ A}$);
- 2) $I_{ave}=761 \text{ A}$, i.e. 75% of cable ampacity;
- 3) $I_{ave}=710 \text{ A}$, i.e. 70% of cable ampacity.

The relevant values of seasonal maxima and averages of load current in % of cable ampacity are listed in Table IV; they are consistent with the typical seasonal load demand in mild climates. Indeed, the highest load level is found in summer, because of the extensive use of air-conditioning systems - despite the more limited usage of lighting devices due to the lowest number of dark hours of the day; maximum current exceeds ampacity from 11:00 a.m. to 6 p.m. reaching the 105% of ampacity according to the summer load profile in Fig. 1. The second average load level is found in winter, because of the extensive use of lighting devices due to the highest number of dark hours, as well as of heating systems due to the coldest climate. The third level is found in autumn, while the lowest load level is found in spring, because of the scarce usage of heating and cooling systems, as well as of lighting devices due to the decreasing number of dark hours.

C. Results

⁶ E.g. in Clause 4.2.3 of [28] a value of $\rho_{T,t}=3.0 \text{ K m/W}$ is reported for “*very dry*” soil conditions and “*little or no rain*” weather conditions.

TABLE IV
SEASONAL MAXIMA AND AVERAGES OF CASE-STUDY LOAD CURRENT

Season ↓	Average yearly load = 80% of ampacity		Average yearly load = 75% of ampacity		Average yearly load = 70% of ampacity	
	Max. [%]	Ave. [%]	Max. [%]	Ave. [%]	Max. [%]	Ave. [%]
spring	82.3	72.5	77.2	68.0	72.1	63.5
summer	105	87.6	98.1	82.1	91.5	76.6
autumn	88.3	77.6	82.8	72.8	77.3	67.9
winter	94.1	82.2	88.3	77.1	82.4	71.9
year	105	80.0	98.1	75.0	91.5	70.0

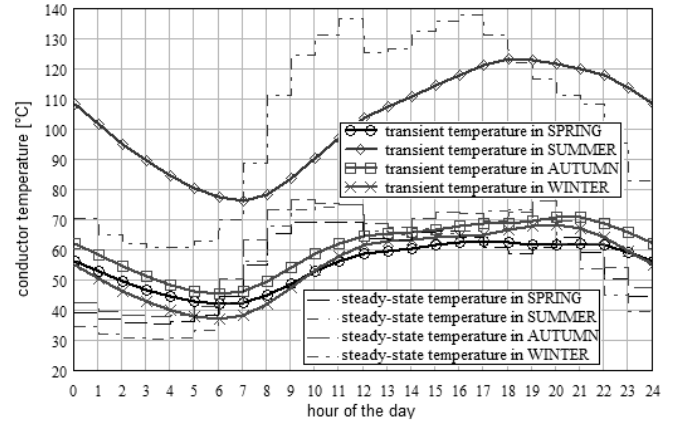


Fig. 2. Transient conductor temperature in the seasonal cycles for the treated cable at average yearly load =80% of ampacity (solid lines with symbols), and steady-state hourly temperatures for each step's current (dashed lines).

TABLE V
MAXIMUM & MEAN VALUES OF TRANSIENT CONDUCTOR TEMPERATURE, $\theta_{c,max}$ AND $\theta_{c,mean}$, PLUS MEAN VALUES OF STEADY-STATE HOURLY CONDUCTOR TEMPERATURE, $\theta_{r,mean}$, FOR ALL SEASONS AND LOAD LEVELS

Season ↓	Ave. yearly load 80%			Ave. yearly load 75%			Ave. yearly load 70%		
	$\theta_{c,max}$ [°C]	$\theta_{c,mean}$ [°C]	$\theta_{r,mean}$ [°C]	$\theta_{c,max}$ [°C]	$\theta_{c,mean}$ [°C]	$\theta_{r,mean}$ [°C]	$\theta_{c,max}$ [°C]	$\theta_{c,mean}$ [°C]	$\theta_{r,mean}$ [°C]
spring	62.6	54.6	54.7	56.8	49.9	50.0	51.6	45.7	45.8
summer	123	102.2	102.7	108	91.4	91.7	95.8	81.9	82.1
autumn	70.7	60.3	60.4	63.6	54.8	54.9	57.3	49.8	49.9
winter	68.3	55.0	55.1	60.7	49.4	49.6	54.0	44.5	44.6

Figure 2 reports the transient conductor temperature $\theta_{i,k}(r_i,t)$ within each j^{th} step ($j=1,\dots,24$) of the hourly cycle of each k^{th} season ($k=1,\dots,4$), calculated for the treated cable at $I_{ave}=812 \text{ A}$ ($= 80\%$ of cable ampacity) with the selected values of cable and soil parameters (solid lines with symbols); the Figure includes the relevant steady-state hourly temperatures $\theta_{j,\infty}$ that would be reached if the current within each j^{th} step was applied steadily (dashed lines without symbols). Figure 2 shows that transient temperature in summer is always far higher than in all other seasons, because of the combination of the highest seasonal load level (see Fig. 1 and Table IV) and of the most unfavorable physical conditions of the soil (see Table III). The distance between the transient temperature curve for summer and those for the other seasons (fairly close to each other) is much greater than the distance between the load curve for summer and those for the other seasons in Fig. 1; this indicates that – in the case-study considered here – the role played by the physical parameters of the soil overwhelms that of the load.

Moreover, in summer the transient temperature exceeds the rated temperature of cable insulation $\theta_D=90^\circ\text{C}$ for most of

the daily cycle, with mean value $\theta_{c,mean}=102.2^\circ\text{C}$ and peak value $\theta_{c,max}=123^\circ\text{C}<130^\circ\text{C}$ ⁷, the emergency operating temperature during extended periods of XLPE-insulated cables [29]) – although it stays well below the highest steady-state temperature of the summer cycle. This paves the way to a dominant role of the life fraction lost in summer, LFS_2 (see (11) being $k=1$ in spring, $k=2$ in summer, $k=3$ in autumn, $k=4$ in winter), vs. other seasons and to a prospective reduction of cable life L_y with respect to design life L_D (see (12)-(14)).

For $I_{ave}=761$ A (= 75% of cable ampacity) and $I_{ave}=710$ A (= 70% of cable ampacity) similar transient temperature curves are obtained that, for each season, are displaced towards lower temperatures, since of course the lower load levels imply lower Joule losses in the conductor, thus lower transient and steady-state temperatures. Such curves are omitted for the sake of brevity, but quantitative elements of transient and steady-state temperatures are given in Table V, which reports for the various seasons and yearly load levels the maximum and mean values of transient conductor temperature, $\theta_{c,max}$ and $\theta_{c,mean}$, as well as the mean values of steady-state conductor temperatures, $\theta_{r,mean}$. Note that the values of $\theta_{c,mean}$ and $\theta_{r,mean}$ are so close that some times more decimal digits are needed to show their difference. The summer values of $\theta_{c,max}$ and $\theta_{c,mean}$ can be taken as a first rough guess of the highest thermal aging rate over the year.

The bar-chart of Fig. 3 displays the life fractions lost in the four seasons, LFS_k ($k=1,\dots,4$), calculated for the treated cable at the selected yearly loads (80%, 75% and 70% of ampacity) for synergism parameter $b_{ET}=0$ K. As expected from Fig. 2 and Table V, the life fraction lost in summer overcomes by orders of magnitude those in the other seasons for all load levels, so that the life fraction lost in the whole year, LFY (see (12)), is unperceptibly higher than that lost in summer. A similar bar chart is obtained for $b_{ET}=4420$ K, but it is omitted since differences between the charts can be hardly detected.

To emphasize such quantitative differences, and to further highlight the role of seasonal factors, Table VI quotes - for all load levels, and for both $b_{ET}=0$ K and $b_{ET}=4420$ K - the values of cable life computed from (10)-(14) with seasonal transient conductor temperature, L_y , as well as the values of cable life obtained with summer transient conductor temperature only, $L_{y,Su}$. The Table shows that, at an average yearly load equal to 80% of ampacity, L_y is much lower than cable design life L_D (40 years), hence summer aging conditions play a quite strong role. When reducing the average yearly load to 75% of ampacity, L_y increases and exceeds L_D , but $L_{y,Su}$ is still lower than L_D . One has to reduce the average yearly load further in order that $L_{y,Su}$ exceeds design life: in fact, when the average

⁷ The thermal life tests on XLPE insulation after [20] – where IPM-Arrhenius life model parameters in Table II come from – were done at 150, 130, 110, 100°C and showed a linear fit in the Arrhenius plot. This indicates that the same thermal degradation reaction (oxidation) dominates over a broad range of temperatures - including 102°C and 123°C - where the IPM-Arrhenius model reasonably holds. Should other degradation modes arise in other case studies - despite the known robustness of the Arrhenius model - other life models (e.g. the Eyring) might be used within the improved procedure.

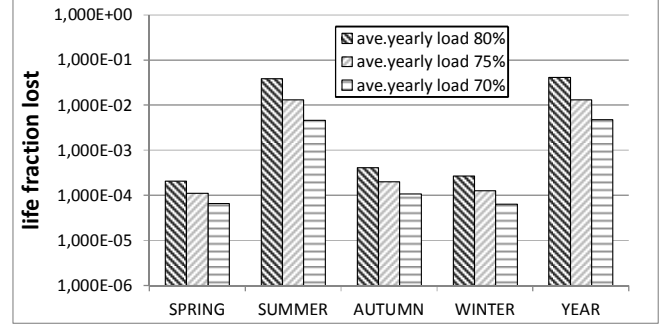


Fig. 3. Life fractions lost in the 4 seasons for the treated cable at average yearly load =80%, 75% and 70% of ampacity. Synergism parameter $b_{ET}=0$

TABLE VI
CABLE LIFE WITH SEASONAL TRANSIENT TEMPERATURE, L_y , AND WITH SUMMER TRANSIENT TEMPERATURE ONLY, $L_{y,Su}$, $b_{ET}=0$ K AND =4420 K

Average yearly load	L_y [y] ($b_{ET}=0$ K)	$L_{y,Su}$ [y] ($b_{ET}=0$ K)	L_y [y] ($b_{ET}=4420$ K)	$L_{y,Su}$ [y] ($b_{ET}=4420$ K)
80%	24.8	6.52	27.7	7.34
75%	75.2	20.0	78.9	21.2
70%	207	56.1	205	55.8

TABLE VII
CABLE LIFE WITH SEASONAL STEADY-STATE TEMPERATURE, L_s , AND WITH SUMMER STEADY-STATE TEMPERATURE ONLY, $L_{s,Su}$, $b_{ET}=0$ AND =4420 K

Average yearly load	$L_{y,r}$ [y] ($b_{ET}=0$ K)	$L_{y,r,Su}$ [y] ($b_{ET}=0$ K)	$L_{y,r}$ [y] ($b_{ET}=4420$ K)	$L_{y,r,Su}$ [y] ($b_{ET}=4420$ K)
80%	10.3	2.69	12.2	3.20
75%	35.7	9.41	39.4	10.5
70%	112	29.8	109	29,3

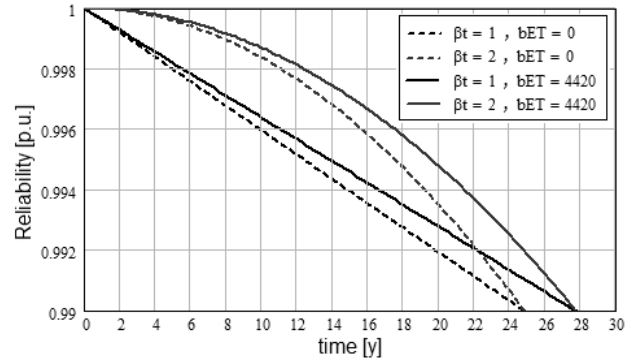


Fig. 4. Yearly reliability vs. service time for the treated cable at yearly load=80% of ampacity, for $\beta=1$ (black lines) and $\beta=2$ (gray lines), as well as for $b_{ET}=0$ (dashed lines) and $b_{ET}=4420$ K (solid lines).

yearly load drops to 70% of ampacity, even cable life in the presence of summer physical conditions of the soil and load exceeds design life significantly. However, at all load levels cable life would be much lower if summer conditions were continuously applied to the cable until failure.

As for the results attained with different values of b_{ET} , as expected $b_{ET}=0$ K yields lower cable life than $b_{ET}=4420$ K, since the former value implies that synergism has the strongest aging effect for $T>T_D$, as occurs in the most critical season, i.e. summer (see Fig. 3). Anyway, when considering that $b_{ET}=4420$ K comes from tests on the treated insulation, it is understood that the worst-case value $b_{ET}=0$ K leads to too conservative life estimates, therefore an experimentally-based value of b_{ET} – if available – is perhaps preferable.

Table VII is the same as Table VI, apart that $L_{y,r}$ (cable life

with seasonal steady-state conductor temperature) and $L_{y,r,Su}$ (cable life with summer steady-state conductor temperature only) are quoted. Table VII shows that with steady-state temperature cable life is much lower for all load levels and aging conditions, despite mean steady-state temperatures and mean transient temperatures are almost equal (see Table V). This is due to the strong non-linearity of the life model (2) which emphasizes the highest temperatures, so that in summer the higher steady-state temperatures overwhelm greatly the effect of the lower transient temperatures (see Fig. 3). This fact points out the need of an accurate calculation of transient temperature for having accurate cable life estimates.

It should be highlighted that cable lifetimes in Tables VI and VII are strongly sensitive with respect to the average yearly load of the cable as this is reduced from 80% to 75%, as well as from 75% to 70%. Such sensitivity has to be addressed to the fact that correspondingly the summer values of $\theta_{c,max}$ and $\theta_{c,mean}$ – which are a first rough guess of the highest thermal aging rate over the year, as pointed out above – decrease by ≈ 10 - 15°C , as shown in Table V. Then, since the Halving Interval in Celsius (HIC)⁸ of XLPE cables tested in [20] is 7.8°C , the decrease in $\theta_{c,max}$ and $\theta_{c,mean}$ caused by the reduction of the load involves roughly a life increase by a factor ranging from, say $2^{15/7.8} \approx 3.79$ to $2^{10/7.8} \approx 2.43$. And actually, e.g., lifetimes L_y obtained for $b_{ET}=0$ K in Table VI increase by ≈ 3 times as the average yearly load of the cable is reduced from 80% to 75%, as well as by ≈ 2.7 times as the average yearly load of the cable is reduced from 75% to 70% – the drop in $\theta_{c,max}$ and $\theta_{c,mean}$ being in fact slightly greater in the former than in the latter case, see Table V.

Of course this approximate reasoning does not account exactly for all strongly non-linear effects associated with detailed transient temperature profiles, electro-thermal stress synergism, etc., which eventually lead to the much more accurate estimates reported in Tables VI-VII.

Figure 4 illustrates – for the cable at average yearly load=80% of ampacity – the trend of yearly reliability R vs. service time t_F , obtained directly from (18), thus based on life L_y and life fraction lost in one year of service LFY (see (12)-(14)). This involves a constant aging rate over the year⁹ equal to the weighted mean of the aging rates in the four seasons. The Figure displays R vs. t_F for $\beta_F=1$ (black lines) and $\beta_F=2$ (gray lines), as well as for $b_{ET}=0$ (dashed lines) and $b_{ET}=4420$ K (solid lines). As expected, Figure 4 shows that R decreases almost linearly within the chosen service time interval for $\beta_F=1$ (since for $\beta_F=1$ one gets an exponential reliability function, whose Taylor series expansion can be truncated at the 1st order term), while R decreases non-linearly with t_F for

$\beta_F=2$. Moreover, Figure 4 confirms that for $b_{ET}=0$ (dashed lines) aging rate is higher and reliability drops faster with t_F than for $b_{ET}=4420$ K (solid lines): in particular, for $b_{ET}=0$ K reliability reaches design value $R_D=1-P_D=0.99$ at $t_F=L_y(b_{ET}=0 \text{ K})=24.8$ y, while for $b_{ET}=4420$ K reaches the design value at $t_F=L_y(b_{ET}=4420 \text{ K})=27.7$ y (see Table VI). Hence, Figure 4 is in full agreement with Table VI and with all previous results.

V. CONCLUSIONS

As proven by the results obtained in the case-study, the improved procedure for life and reliability estimation of HVAC cables subjected to load cycles including the effects of seasonal factors works properly, being sensitive to the various seasonal factors – i.e. load current, soil temperature and thermal resistivity – in a proper way. This fulfills the first goal of the paper (see Section I).

As far as the second goal of the paper is concerned, it is also fulfilled since the procedure provides results consistent with the increase of cable failure rates under heat waves experienced by utilities in service, thereby singling out criticalities that might arise if seasonal factors are not properly taken into account. The results prove that seasonal factors – especially soil thermal resistivity and temperature – have a major effect on life and reliability of typical HVAC cables under load cycles. Thus their accurate representation is essential, together with the correct simulation of thermal transients and the use of proper electro-thermal life models.

Of course, the results obtained here should be regarded with care. Indeed, the procedure is based on some assumptions, the most critical being the selection of average seasonal factors for soil thermal resistivity and temperature, as well as for 24-h daily load cycles. Anyway, the procedure can work also with averages on much shorter periods – at the price of longer computing time. This enables an accurate scanning of changes of the load and of the physical state of the soil within every season, by using e.g. monitored data of daily load and of soil temperature and humidity.

In the future the procedure will be improved following the cumulative aging approach, so as to drop progressively some simplifications and be capable of treating: full cable systems (including accessories beside cable lengths), voltage surges, thermomechanical stresses, weekdays vs. weekends, load changes over the years and partial drying of the soil.

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⁸ The Halving Interval in Celsius (HIC) is the temperature increase which yields a halving of time-to-failure of an insulation starting from the temperature of the TI. In turn the TI (Temperature Index) is the Celsius temperature corresponding to a time-to-end-point of 20,000 hours, equal to 101°C for the tested XLPE insulation.

⁹ Seasonal reliability R_s , which accounts for the different seasonal aging rates, can be derived via a more complicated procedure – omitted for brevity.

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