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A New Approach to the Inverse Power Model in Qualification Load Cycle Planning and Life Estimation for HVDC Extruded Cables

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***Abstract*— Cigrè Technical Brochure 852:2021 has confirmed the voltages and durations of qualification load cycles for HVDC extruded cables as in former Technical Brochures 219:2003 and 496:2012. These values rely on the Inverse Power Law Model with life exponent set to *n*=10, considered in Cigrè 852 a conservative basis for estimating cable life. The value *n*=10 has been left unchanged over more than 20 years to date despite new compounds with *n* up to 26 have emerged thanks to the technological improvement of polymeric DC cable insulation. Relying on this Technical Brochure 852, so far the author has used the same approach to estimate the life of HVDC extruded cables under qualification test load cycle conditions. This paper proposes a new approach to the Inverse Power Model in the selection of voltage levels and durations of qualification load cycles. Such new approach exploits the evidence that qualification tests are passed with broad margin by "good" cable systems, and highlights the improved voltage endurance of new cable insulation compounds with greater *n*. The satisfactory performance of this approach on both these respects is proven by an illustrative application to life estimation of HVDC cables subject to type test load cycles.**

***Index Terms*-- HVDC insulation, Life estimation, Power cables, Qualification, Reliability estimation, Testing, XLPE.**

I. INTRODUCTION

The technological improvements of HVDC extruded cable systems in the last 25 years has led to very high voltage and power ratings. Some examples in the European Union are:

1) the ±400 kV-DC/1 GW submarine Nemo Link between Belgium and UK, operated with Voltage Source Converters (VSC), commissioned in 2019 [1];
2) the three ±525 kV-DC/2 GW land German Corridors, [2], to be operated with VSC [3];
3) the ±525 kV-DC/1 GW submarine Adriatic Link in Italy, to be operated with VSC [4];
4) a section of the ±400 kV-DC/600 MW Kontek Link between Germany and Denmark, operated with Line Commutated Current Source Converters (LCC); this is the world's first 400-kV LCC extruded cable system [5].

The progress of HVDC extruded cable systems over the years has also been made possible by thorough testing procedures, enhanced over time to assess the performance of innovative designs, materials and manufacturing techniques of cable system components. For HVDC extruded cable systems the reference to date is Cigrè Technical Brochure (TB) 852:2021 [6], which – in line with former TB 219:2003 [7] and TB 496:2012 [8] – emphasizes the role of qualification (i.e. prequalification and type) load cycles to assess the long term performance of HVDC extruded cable systems in the presence of the typical daily cycles of conductor current.

TB 852, issued in 2021, has confirmed the same voltage levels and durations of prequalification test (PQT) and type test (TT) load cycles as in TB 219:2003 [7] and TB 496:2012 [8]. The rationale for this choice, illustrated in detail in Appendix A of TB 852 [6], is based on the selection of the Inverse Power Law Model - or simply Inverse Power Model (IPM) - for cable system life estimation under applied voltage, with a cable system design life of 40 years at rated voltage U_0 and a value for life exponent n equal to 10. This latter value was estimated since 2003 by Cigrè Working Groups as a lower conservative limit for n [6]-[8]. This same approach is also followed by TB 852 for the Extension of Qualification Test (EQT) load cycles; the EQT is introduced for the first time in TB 852 as a shorter alternative to the PQT to demonstrate satisfactory long-term performance of an already prequalified cable system [6].

Based on this authoritative reference, so far the author of this paper has used the same approach to estimate the life of HVDC extruded cables in the presence of PQT load cycles [9],[10] and TT load cycles [11]. The approach has proven to be successful. Indeed, the life estimates for HVDC extruded cables under qualification load cycle conditions obtained with this approach are all fairly longer than the duration of qualification load cycles (i.e. 360 days for the PQT and 30 days for the TT); this result is in line with the clear evidence that qualification tests are successfully passed by well designed, manufactured and installed cable systems, without breakdown of cable system components and with no signs of detrimental deterioration for the system operation revealed by the final examination [6].

Anyway the value of n=10 has been left unchanged by TB 219:2003 [7], TB 496:2012 [8] and TB 852:2021 [6] over more than 20 years to date despite new compounds with n up to 26 have emerged in the market over these years [12]-[15].

This paper investigates a possible new approach to the use of the Inverse Power Model (IPM) in the selection of voltage levels and durations of qualification (PQT, EQT and TT) load cycles. Such new approach on the one hand exploits the above-cited evidence that PQT, EQT and TT load cycles are passed successfully by well designed, manufactured and installed cable loops, and on the other hand highlights the improved voltage

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endurance of new materials with greater life exponent.

The paper is structured as follows. Section II shows the theoretical-empirical background whereby the limits of the present approach to the IPM followed in TB 852 can be pointed out and the new approach can be derived. Section III summarizes the life and reliability estimation procedure for HVDC cables under qualification load cycles used so far, based on the same approach as in TB 852. Section IV proposes a new approach to the IPM that might replace the one in TB 852 for the selection of qualification test voltages at set values of qualification test durations; this new approach suggests some new sets of values for the voltage levels of the qualification load cycles, depending on the declared value of *n*. The new approach not only stays in line with the above evidence that qualification tests are successfully passed by "good" cable systems, but also highlights the improved voltage endurance of new insulations with higher *n*. Section V applies this same approach to the HVDC cable life estimation procedure under load cycles, and reports an application of such new approach to a 500 kV DC-XLPE cable subject to TT load cycles, showing its satisfactory performance on both these respects (qualification load cycles are passed by good cables and the greater *n*, the better the cable voltage endurance). Section VI discusses the limits of the old and new approach and Section VII draws conclusions also in the perspective of future issues of Cigrè TB 852 and IEC 62895.

II. INCONSISTENCIES IN THE APPROACH OF TB 852 TO LIFE ESTIMATION ACCORDING TO THE INVERSE POWER MODEL

The IPM – a life model broadly employed in many different fields of applied physics for its simplicity, flexibility and effectiveness – is used in many different forms. For cable insulation, it is often expressed as the so-called "Voltage-time" (or "V-t") characteristic, as in Appendix A of TB 852 [6]:

$$V^n t = \text{constant} \tag{1}$$

where *V* is applied voltage, *t* is cable system time to failure (or life), *n* is life exponent. Appendix A of [6] points out that "*the approach requires knowledge of ... n which is determined empirically from endurance tests on cables*", emphasizing the main role played by cables in this approach, notwithstanding the importance of accessories in the behavior of cable systems.

The IPM (1) is better recast in terms of reference values of voltage and life. E.g. in Appendix A of [6], "*to determine the test voltage factors that are equivalent to a prescribed system life when testing for a shorter time*", (1) is in fact rewritten as[1]:

$$t_1 = t_0 (V_{dc}/V_0)^{-n} \tag{2}$$

where V_{dc} is test voltage, V_0 (=U_0) is system voltage, t_0 is design life and t_1 is test duration. From (2), Appendix A of [6] derives the test voltage ageing factor K_1 as follows:

$$K_1 = \sqrt[n]{t_0/t_1} \tag{3}$$

Thereafter, by setting design life t_0=40 years=40×365 days and *n*=10, the following values of qualification test voltages are derived, as summarized in Clause 1.5.3 and Table 8 of [6]:

1) K_1=1.45, $V_{dc}=U_{TP1}$=1.45U_0 for t_1=360 days of PQT load cycles;
2) K_1=1.68, $V_{dc}=U_{EQ1}$=1.68U_0 for t_1=82 days of EQT load cycles;
3) K_1=1.85, $V_{dc}=U_T$=1.85U_0 for t_1=30 days of TT load cycles.

The IPM in the form of (2) with t_0=40 years=14600 days and *n*=10 can be referred to as the IPM after TB 852 [6].

The IPM provides straight lines in log-log coordinates, where it becomes clear that the higher the VEC *n*, the better the electrical endurance of the insulation, as explained more in detail below [16]. This theoretical argument is confirmed by the experimental evidence that insulating materials having greater value of *n* also exhibit better voltage endurance properties, as shown e.g. in Fig. 4 of [13]; for this reason *n* is referred to also as "Voltage Endurance Coefficient" (VEC) [17].

Yet, as pointed out in [16], the consequences of the use of the IPM are sometimes misunderstood, not only in technical-scientific papers, but also in Cigrè TBs and IEC Standards. Indeed, the examples reported in Table I of [18] show that Cigrè and IEC documents - following the same approach as in (2), (3) - lead to the unexpected result that the greater is *n*, the lower is the test factor K_1 for both PQT and TT, e.g.:

- Cigrè TB 853 hypothesizes implicitly *n*=11 for HVDC lapped cables, thus establishing K_1=1.4, $V_{dc}=U_{TP1}$=1.4U_0 for t_1=360 days (PQT load cycles), K_1=1.8, $V_{dc}=U_T$=1.8U_0 for t_1=30 days (TT load cycles), see Clause 1.5.3 of [19];
- IEC 62067 hypothesizes implicitly *n*=7 for EHVAC extruded cables, thus establishing a value of K_1=1.7 for PQT load cycles [20].

It is readily seen from these instances that, surprisingly, in the case of PQT load cycles K_1=1.4 for *n*=11 [19], K_1=1.45 for *n*=10 [6], K_1=1.7 for *n*=7 [20]. Such seemingly-strange behavior – when considering the previous comment that insulating materials having greater value of *n* also exhibit better voltage endurance properties – is worth being analyzed more deeply, so as to learn something more about the IPM and its key parameters for cable insulation design and qualification testing, i.e. life exponent *n* , test duration t_1 and test voltage V_{dc}.

Starting from design, let us consider the typical log(*V*) vs. log(*t*) coordinate system for the IPM shown in Fig. 1(a). Here (2) yields a straight line with slope −1/*n*, implying that - for the same value of V_{dc} and t_1 - the higher is *n*, the longer will life be for voltages below V_{dc}, in particular for system (design) voltage V_0. As seen in Fig. 1(a), let us consider two insulations A and B

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[1] Let us use the same symbols of test voltages and durations as in TB 852 [6].

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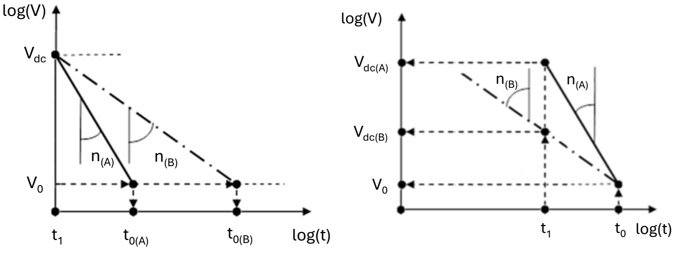
tested with same voltage V_{dc} and duration t_1, but having $n_{(B)} > n_{(A)}$: then, at design voltage V_0 the design life of material B, $t_{0(B)}$, will be longer than that of A, $t_{0(A)}$ - as highly desired by cable manufacturers and utilities [15]. Thus, the IPM implies that the higher is *n*, the better the insulation endurance, i.e. its ability to endure electric stress down to the design level.

Coming now to qualification testing, as done in Appendix A of [6] - and in [19],[20] - test voltage V_{dc} is selected starting from given values of design voltage V_0, design life t_0 and test duration t_1: for practical reasons $V_{dc} >> V_0$, as $t_1 << t_0$, namely test duration shall be much lower than design life. Then, for two insulations with the same values of V_0, t_0 and t_1 relationship (2) – or its equivalent (3) – implies that the higher is *n*, the lower will test voltage V_{dc} be. For example, as shown in Fig. 1(b), let us consider the same insulations A and B with $n_{(B)} > n_{(A)}$, but now – differently from Fig. 1(a) – the same value of V_0 and t_0: then a test duration t_1 implies a test voltage of material B, $V_{dc(B)}$, that is lower than that of material A, $V_{dc(A)}$. This leads to the apparent paradox that the better the electrical endurance of a given insulation, the lower should its qualification test voltage be for fixed values of design voltage, design life and test duration [16]. Hence, the test voltage seems to be not consistent with the better voltage endurance of insulating materials that have a greater value of *n*.

To show the practical consequences of this inconsistency, let us compare the IPM after TB 852 [6] - i.e. (2) with t_0=40 y and *n*=10 - with the same IPM using 3 greater values of *n* = 12.5, 15, 17 - supported by the values from [15] and Fig. 3 of [17] (taken in turn from [21]). The comparison is shown in Fig. 2, where the IPM lines according to (2) are plotted for *n*=10 (IPM after TB 852, light gray dashed), 12.5 (light gray solid), 15 (dark gray solid), 17 (black solid). The points at design (box), PQT (diamond), EQT (circle) and TT (cross) conditions according to [6] are also shown. The semi-log plot is used to broaden the voltage interval from 1 to 2 in p.u. of U_0. It is seen that Fig. 2 is consistent with Fig. 1(b): indeed, the values of life obtained from (2) at TT, EQT, PQT voltages for *n*=12.5, 15, 17, are all lower than those obtained with *n*=10, i.e. the IPM after TB 852: the greater *n*, the lower the values of test voltages for the various test durations. The value of life at design voltage is the same for all values of *n*, as design conditions correspond to the common point of IPM lines in Fig. 1(b) and in Fig. 2.

The values of qualification test voltages (with 3 decimal digits) obtained from (2) for t_0=40 y and *n*=10 (IPM after [6]), 12.5, 15, 17 with the various test durations set in TB 852 [6] are summarized in Table I, where design conditions at U_0 are also reported for the sake of completeness. Table I confirms that the test voltages obtained from (2) for *n*=12.5, 15, 17 for the TT, EQT, PQT durations set in TB 852 [6] are progressively lower than those for *n*=10, i.e. the IPM after TB 852: the greater *n*, the lower the values of test voltages for the various test durations.



(a) (b)

Fig. 1. IPM in log(*V*) vs. log(*t*) coordinates for cable insulating materials A and B with $n_{(B)} > n_{(A)}$, and: (a) same value of V_{dc} at test duration t_1, but different values of design life t_0 at design voltage V_0 ; (b) same value of t_0 at V_0, but different values of test voltage V_{dc} at test duration t_1.

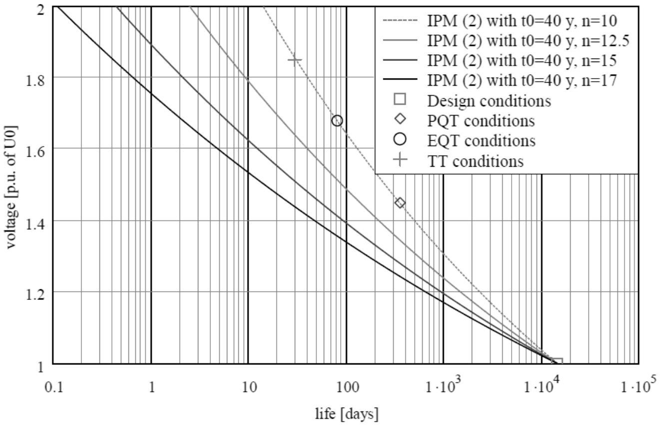


Fig. 2. IPM according to (2) (lines) for t_0=40 y and *n*=10 (IPM after TB 852 [6], light gray dashed), 12.5 (light gray solid), 15 (dark gray solid), 17 (black solid). The points at design (box), PQT (diamond), EQT (circle) and TT (cross) conditions according to TB 852 are also shown.

TABLE I VALUES OF QUALIFICATION TEST VOLTAGES (WITH 3 DECIMAL DIGITS) ATTAINED FROM (2) FOR t_0=40 Y AND *n*=10 (IPM AFTER [6]), 12.5, 15, 17 WITH THE TEST DURATIONS SET IN TB 852 FOR THE TT, PQT, EQT [6]

Test	Test duration [days] set in TB 852 [6]	Test voltage [p.u. of U_0] from (2) vs. *n*			
		n=10	*n*=12.5	*n*=15	*n*=17
TT	30	1.857	1.641	1.511	1.439
EQT	82	1.679	1.514	1.413	1.356
PQT	360	1.448	1.345	1.28	1.243
Design	365×40=14600	1	1	1	1

TABLE II VALUES OF QUALIFICATION TEST DURATIONS ATTAINED FROM (2) FOR t_0=40 Y AND *n*=10 (IPM AFTER [6]), 12.5, 15, 17 WITH THE QUALIFICATION TEST VOLTAGES SET IN TB 852 FOR THE TT, PQT, EQT [6]

Test	Test voltage [p.u. U_0] set in TB 852 [6]	Test duration [days] from (2) vs. *n*			
		n=10	*n*=12.5	*n*=15	*n*=17
TT	1.85	31.1	6.68	1.44	0.42
EQT	1.68	81.5	22.3	6.09	2.16
PQT	1.45	355	140	55.4	26.4
Design	1	14600	14600	14600	14600

As can be seen from Table 8 of [6], the test voltages obtained for *n*=10 and reported in TB 852 are actually rounded to two decimal digits with respect to those in Table I, and the rounding is not on the safe side in the case of TT; however, since the IPM is very sensitive to even small variations of voltage *U*, the effect of such rounding is non-negligible. This is proved by Table II, which reports for the test voltages after TB 852 the corresponding actual values of test durations obtained from (2) for t_0=40 y and *n*=10 (IPM after [6]), 12.5, 15, 17. Table II demonstrates first of all that for *n*=10 the values of test voltages rounded to two digits and reported in TB 852 provide test durations that are sensibly different from those set in TB 852 itself – compare column 3 of Table II with column 2 of Table I – emphasizing the strong sensitivity of the IPM to small voltage changes as those involved in the rounding procedure. Secondly Table II highlights that, when using (2) for *n*=12.5, 15, 17, the test durations obtained with the test voltages reported in TB 852 are progressively lower than the durations established in TB 852 for *n*=10: the greater *n*, the lower the test durations with respect to those set in TB 852. This is against the testing evidence that State-of-the-Art (SoA) DC extruded cable systems – which have all cable insulation with *n* well above 10 – do pass qualification load cycles without any problem if they are well designed, manufactured and installed.

Trivially, Tables I and II prove that for all values of *n*:

- design life t_0=40 y yields design voltage U_0;
- design voltage U_0 yields design life t_0=40 y.

This is because design conditions correspond to the common point of IPM lines in Fig. 1(b) and in Fig. 2.

In summary, as hinted at above, the behavior illustrated in Fig. 1(b) and 2, as well as in Tables I, II, is not consistent with the above-mentioned theoretical argument and experimental evidence that insulating materials having greater value of *n* also exhibit better voltage endurance properties, as shown in Fig. 4 of [13], and that the relevant cable systems do pass qualification tests according to TB 852.

III. HVDC CABLE LIFE ESTIMATION PROCEDURE FOR QUALIFICATION LOAD CYCLES FOLLOWING THE APPROACH OF TB 852

Similar equations to (1), (2) can be written by replacing voltage *V* (or *U*) with the electric field *E* within the insulation of the cable, to estimate the "electrical life" of the various points of the insulation – in practice the time to the onset of a damaged zone large enough to trigger an electrical tree, which will lead insulation to failure quite soon [22],[23]. The most severely stressed point within cable insulation – i.e. that where electrical life is the shortest – is also the point where failure is likely to start from, thus determining the time-to-failure (=life) of the whole cable [17],[18].

Cable insulation temperature is typically greater than the ambient temperature, thereby leading to electro-thermal stress and electro-thermal aging. Hence, the IPM after TB 852 can be recast to account for such electro-thermal stress, giving rise to the so-called IPM-Arrhenius electro-thermal life model. This is the model used in the life and reliability estimation procedure for HVDC cables under qualification load cycles, set up and validated for PQT cycles in [9],[10] and for TT cycles in [11].

In summary, the procedure has 4 stages.

1) Calculation of transient temperature across insulation wall throughout qualification load cycles, *T*(*r*,*t*), where *r*= insulation radius and *t*=time during qualification load cycles. *T*(*r*,*t*) is computed following IEC 60853-2 [24];
2) Calculation of transient electric field across insulation wall throughout qualification load cycles, *E*(*r*,*t*). In the procedure, *E*(*r*,*t*) is computed using two methods:
   i) a "rigorous" method, consisting in the numerical solution of Maxwell's Equations, i.e. [10]:

$$\nabla \cdot (\varepsilon \boldsymbol{E}) = \rho \tag{4}$$

$$\nabla \cdot \boldsymbol{J} = -\partial\rho/\partial t \tag{5}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} \tag{6}$$

$$\sigma = \sigma_0\, exp(a(T - T_0) + b(E - E_0)) \tag{7}$$

where:

- $\boldsymbol{E}$ = electric field vector;
- $\boldsymbol{J}$ = conduction current density vector;
- ρ = density of free charges;
- σ = cable insulation electrical conductivity;
- σ_0= σ at T_0=0°*C* and E_0≈0 kV/mm;
- a = temperature coefficient of σ;
- b = field coefficient of σ;
- ε = permittivity of the dielectric.

   ii) an approximate method based on the steady-state analytical formula developed by Eoll [25]:

$$E(r) = U_0 \frac{\delta}{r_o[1 - (r_i/r_o)^{\delta}\,]}\ (r/r_o)^{\delta-1} \tag{8}$$

$$\delta = \frac{\dfrac{aW_c}{2\pi\lambda_{T,d}} + bE_m}{1 + bE_m} = \frac{\dfrac{a\Delta T_d}{\ln(r_o/r_i)} + \dfrac{bU_0}{r_o - r_i}}{1 + bU_0/(r_o - r_i)} \tag{9}$$

where:

- r_i , r_o = inner , outer insulation radius;
- δ = field inversion coefficient;
- W_c = per unit length conductor Joule losses;
- ΔT_d = temperature drop across cable insulation
- $\lambda_{T,d}$ = thermal conductivity of the insulation;
- E_m = average field within the insulation.

3) Cable life evaluation under qualification load cycles. It relies on the above-mentioned electrothermal IPM-Arrhenius life model [17], cast into Miner's law of cumulated aging [26] as per (10)-(13) to estimate at each insulation radius *r*: $LF_{cycle}(r)$ = life fraction lost during one qualification load cycle lasting t_d=1 day; $K_{cycle}(r)$ = number of cycles-to-failure; $L_{cycle}(r)$ = time-to-failure; as well as the life L_{cycle} of the point of cable insulation with shortest life (= greatest electro-thermal stress), which – as hinted at above – determines the cable's overall time-to-failure:

$$L(E,T) = L_D(E/E_D)^{-(n_D - b_{ET}T'')}(E_D/E_0)^{b_{ET}T''}\ e^{-BT''} \tag{10}$$

$$LF_{cycle}(r) = \int_0^{t_d} \frac{dt}{L[E(r,t),T(r,t)]} = \frac{1}{K_{cycle}(r)} \tag{11}$$

$$L_{cycle}(r) = t_d \times K_{cycle}(r) \tag{12}$$

$$L_{cycle} = min\{L_{cycle}(r), r \in [r_i, r_o]\} \tag{13}$$

where:

- $L[E(r,t),T(r,t)]$ = life at $E(r,t)$ and $T(r,t)$;
- T''=1/T_D–1/T = conventional thermal stress;
- E_D = design field of cable insulation;
- T_D = design temperature of cable insulation;
- L_D = design life of cable insulation;
- n_D = design value of life exponent at T=T_D;
- b_{ET} = synergy factor of *E* vs. *T* stress;
- *B* = thermal degradation activation energy.

4) Reliability evaluation. HVDC cable reliability under load cycles, R_{cycle}, is predicted assuming that L_{cycle} is a Weibull RV - with shape parameter β_t - corresponding to design failure probability P_D. Then, after some manipulations one obtains cable reliability at a time t_F under load cycles, $R_{cycle}(t_F)$, via (14).

$$R_{cycle}(t_F) = \exp\{-(t_F / L_{cycle})^{\beta_t}[-\ln(1-P_D)]\} \qquad (14)$$

As hinted above, the electro-thermal IPM-Arrhenius model (10) employed so far in the procedure is based on Appendix A of TB 852, as it uses the following key values [9]-[11]:

- L_D = 40 years = cable insulation design life at U_0, i.e. the same as t_0 at system voltage V_0 in Appendix A of [6];
- n_D = 10 = life exponent at design temperature T_D, i.e. the same as n in Appendix A of [6];

with E_D (which in (10) replaces V_0 found in (2)) and T_D chosen as the field and temperature at the most stressed insulation point when the cable is subjected to (see [6] Clauses 1.5.3 and 1.5.4):

- U_0 = "*rated continuous DC voltage between conductor and … screen for which the cable system is designed*";
- $T_{cond,max}$ = "*maximum temperature at which the cable conductor is designed to operate*";
- ΔT_{MAX} = "*maximum temperature difference over the cable insulation in steady state at* $T_{cond,max}$ *… at which the cable is designed to operate*".

However - as witnessed by Fig. 1(b) and 2 - this approach leads to the inconsistency that, if values of n_D >10 are taken to account for the technical progress on voltage endurance of DC cable insulation, the values of life obtained from (10) at constant values of E, T, as well from (10)-(13) under load cycles, are lower than those obtained with n_D =10.

A possible "physical" explanation for this paradoxical behavior is that setting design life L_D=40 y at design field E_D and temperature T_D of the insulation (or equivalently at system voltage V_0 of the cable, as in Appendix A of [6]) is not supported by any experimental evidence, since tests lasting t_0=L_D=40 y are of course unfeasible. However, a survey on HV cable failures over the period 2006-2015 reported in Cigrè TB 815 [27] quotes a failure rate of 0.029 faults/y/100 km for submarine HVDC MIND cables, and of 0 faults/y/100 km for submarine HVDC extruded cables (no data are given for land cables, see Table 28 of [27])[2]. Therefore, when considering the so-called enlargement effect – whereby the greater the volume, the higher the number and size of defects in the enlarged insulation, the smaller the life at a given value of cable reliability – the actual value of L_D=t_0 might be much longer than 40 years. This holds a fortiori for qualification test loops, which are much shorter than cable lines installed on site.

On the contrary, TT load cycles last 30 days only and show that well designed, manufactured and installed cable systems do pass such tests with a broad margin. This suggests to apply the converse approach illustrated in Fig. 1(a) to the IPM, to change:

1) the derivation of qualification test voltages with respect to the present approach in Appendix A of [6];
2) the IPM-Arrhenius model (10) used so far in the DC cable life estimation procedure under load cycles.

IV. A NEW APPROACH TO THE INVERSE POWER MODEL FOR THE CHOICE OF QUALIFICATION LOAD CYCLE VOLTAGES

Then let us first apply the converse approach illustrated in Fig. 1(a) to the IPM to change the derivation of qualification test voltage with respect to Appendix A of [6]. This can be done rewriting (2), (3) as follows:

$$t_1 = t_T(V_{dc}/U_T)^{-n} \qquad (15)$$

$$K_1 = \sqrt[n]{t_T/t_1} \qquad (16)$$

where t_1 and V_{dc} are still test duration and voltage, while TT voltage U_T=1.85U_0 has replaced system voltage V_0 (=U_0), and TT load cycles duration t_T=30 days has replaced design life t_0.

As far as (15), (16) are concerned, let us point out that:

- the duration t_1 of qualification load cycles for EQT and PQT can be kept respectively at 82 days and 360 days as in TB 852, since these durations are well established and in line with practical requirements related to space and time management during testing;
- there is no more need to set the life exponent necessarily to the lower limit n=10 in Appendix A of [6]: greater values can be taken to account for the technological improvement of HVDC extruded cable insulation.

To illustrate the practical consequences of this simple, but highly innovative approach summarized by (15),(16) as a replacement for (2),(3) used in Appendix A of [6], let us analyze (15),(16) parametrically as done previously for (2),(3) considering the same 3 possible values of n>10, namely n=12.5, 15, 17, and compare them with n=10 after [6], as done in former Fig. 2 and Tables I,II. The comparison is shown in Fig. 3, where the IPM lines according to (15) are plotted for n=10[3] (light gray dashed), 12.5 (light gray solid), 15 (dark gray solid), 17 (black solid). The points at design (box), PQT (diamond), EQT (circle) and TT (cross) conditions according to TB 852 are also shown. The semi-log plot focuses on voltages from 1 to 2 in p.u. of U_0. It is readily seen that Fig. 3 is consistent with Fig. 1(a). Indeed, the values of life obtained from (15) at EQT, PQT and design voltages for n=12.5, 15, 17, are all greater than those obtained for n=10: the greater n, the greater the values of test voltages for the various test durations. The value of life at TT voltage is the same for all values of n, as TT conditions correspond to the common point of IPM lines in Fig. 1(a) and Fig. 3.

The values of qualification test voltages obtained from (15) for n=10, 12.5, 15, 17 with the various test durations set in TB 852 [6] are summarized in Table III, where design conditions at U_0 are also reported for the sake of completeness. Table III confirms that the test voltages obtained from (15) for n=12.5, 15, 17 for the durations of the TT, EQT, PQT set in TB 852 are progressively greater than those obtained for n=10: the greater

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[2] This makes sense as HVDC extruded cables are generally in service since much shorter time than HVDC MIND cables, thus failures not recorded in [27] might occur later in HVDC extruded cables

[3] It can be easily demonstrated that (15) for n=10 is essentially equivalent to the IPM after TB 852 [6].

n, the greater the values of test voltages for the various test durations.

Table IV reports for the test voltages after TB 852 the corresponding actual values of test durations obtained from (15) for *n*=10, 12.5, 15, 17. Table IV highlights that, when using (15), for *n*=12.5, 15, 17 the durations of EQT and PQT with the test voltages set in TB 852 are progressively greater than those obtained for *n*=10 and set in TB 852: the greater *n*, the greater the test durations with respect to those set in TB 852. Moreover, Table IV indicates that design life at design voltage U_0 increases progressively with *n* compared to the 40 years set in TB 852. This is the reason why – among other technological targets – manufacturers have striven over the years to raise the value of the life exponent for HVDC extruded cables [15],[23]: e.g. from *n*=9 in [28] to *n*=15/19 in [21], up to *n*=26 in [13],[14] – the same DC-XLPE as that used in the Nemo link [1].

Trivially, Tables III and IV prove that for all values of *n*:

- TT duration t_T=30 days yields TT voltage U_T;
- TT voltage U_T yields TT duration t_T=30 days.

This is because TT conditions correspond to the common point of IPM lines in Fig. 1(a) and Fig. 3.

Again Tables III, IV emphasize the sensitivity of the IPM to small variations of voltages like those involved in the rounding procedure. Indeed, former Tables I and II have shown that the IPM in the form of (2) with *n*=10 yields a value of U_T=1.857U_0 at t_T=30 days, whereas the rounded value U_T=1.85U_0 provides a value of t_T=31.1 days; since the values set in the IPM in the form of (15) are U_T=1.85U_0 and t_T=30 days – in line with TB 852 – relationship (15) for *n*=10 is such that:

- design life L_0=40 y=14600 days yields a design voltage of 0.996U_0, i.e. slightly lower than U_0;
- design voltage U_0 yields a design life L_0=14088 days=38.6 years, i.e. slightly less than 40 y.

Overall, Fig. 3 and Tables III, IV are in fair agreement with the above-described testing evidence that cable insulations with greater *n* have better voltage endurance than those with smaller *n*. They are also in line with the fact that SoA DC extruded cable systems – which in fact have all *n* well above 10 [13]-[15], [17],[21] – do pass qualification tests without problems if well designed, manufactured and installed. For this reason, the new approach suggests a set of new possible values for qualification test voltages, provided that a certain value of *n is* declared. For example, Table V lists some sets of possible prospective values of qualification test voltages attained from (15) with the test durations set in TB 852 [6] for DC extruded cable insulation whose declared values of life exponent are *n*=10, 12.5, 15, 17 (of course for *n*=10 the same values as in [6] are obtained).

Then, following this new approach, if a cable system passes qualification load cycles under the test voltages listed in Table V, this not only demonstrates its satisfactory behavior under the time-varying electro-thermal-mechanical stress produced by qualification load cycles, but also indicates that cable insulation possesses the declared value of life exponent; this proves – via a challenging test on a full-size cable loop including accessories – the good long-term voltage endurance properties of cable insulation associated with that declared value of *n*, which are typically assessed only via tests on smaller objects - flat specimens or mini-cables [15]. Hence the voltages listed in Table V might be useful also for internal R&D tests to be carried out by manufacturers on cable loop prototypes [15].

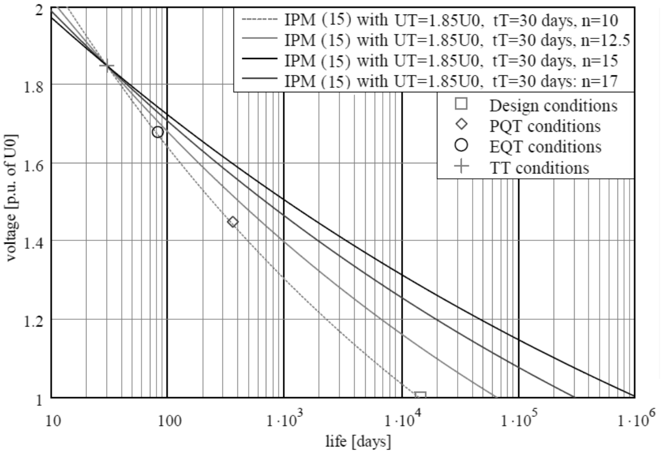

Fig. 3. IPM according to (15) (lines) for *n*=10 (equivalent to the IPM after TB 852 [6], light gray dashed), 12.5 (light gray solid), 15 (dark gray solid), 17 (black solid). The points at design (box), PQT (diamond), EQT (circle) and TT (cross) conditions according to TB 852 are also shown.

TABLE III Values of Qualification Test Voltages (with 3 Decimal Digits) Attained from (15) for *n*=10, 12.5, 15, 17 with the Test Durations Set in TB 852 for the TT, PQT, EQT [6]

Test	Test duration [days] set in TB 852 [6]	Test voltage [p.u. of U_0] from (15) vs. *n*			
		n=10	*n*=12.5	*n*=15	*n*=17
TT	30	1.850	1.850	1.850	1.850
EQT	82	1.673	1.707	1.730	1.744
PQT	360	1.443	1.516	1.568	1.598
Design	365×40=14600	0.996	1.128	1.225	1.286

TABLE IV Values of Qualification Test Durations Attained from (15) for *n*=10, 12.5, 15, 17 with the Qualification Test Voltages set in TB 852 for the TT, PQT, EQT [6]

Test	Test voltage [p.u. U_0] set in TB 852 [6]	Test duration [days] from (15) vs. *n*			
		n=10	*n*=12.5	*n*=15	*n*=17
TT	1.85	30	30	30	30
EQT	1.68	78.7	100	127	154
PQT	1.45	343	630	1159	1.887
Design	1	14088	65579	305279	1.045E+6

TABLE V Prospective Qualification Test Voltages Attained from (15) for the Test Durations Set in TB 852 [6] for DC Extruded Cable Insulation with Declared Values of Life Exponent *n*=10, 12.5, 15, 17.

Test	Test duration [days] set in TB 852 [6]	Test voltage [p.u. of U_0] proposal vs. *n*			
		n=10	*n*=12.5	*n*=15	*n*=17
TT	30	1.85	1.85	1.85	1.85
EQT	82	1.68	1.71	1.73	1.75
PQT	360	1.45	1.52	1.57	1.60

V. The New Approach to the IPM in the Life Estimation Procedure for HVDC Cables under Load Cycles

Let us adopt now this same innovative approach also for the IPM-Arrhenius model used in the life estimation procedure for HVDC cables under qualification load cycles. In order to do this, let us recast the IPM-Arrhenius model (10) as follows:

$$L(E,T) = t_T (E/E_{TT})^{-(n_D - b_{ET}T'')} (E_{TT}/E_0)^{b_{ET}T''} \, e^{-BT''} \quad (17)$$

According to the new approach to the IPM, in (17) the following quantities have been replaced compared to (10):

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- L_D with t_T=30 days = duration of TT load cycles [6];
- E_{TT} = electric field at the most-severely stressed point within insulation thickness at TT voltage U_T=1.85U_0 when the conductor is at its rated temperature $T_{cond,max}$.

The advantages of this new approach compared to the former used in [9]-[11] is shown here by applying the old and the new version of the life estimation procedure for HVDC cables under qualification load cycles to a 500-kV VSC DC-XLPE insulated cable with main design parameters listed in Table VI. Similarly to Section IV, the application consists in estimating cable life under TT load cycles for VSC cables via the old and new procedure with the life exponent set to n_D = 10, 12.5, 15, 17, 26; the last value, taken from [13],[14] is added to those in Section IV as an example of top life exponent for SoA DC-XLPE (of the filled type in [13],[14]). All estimates are obtained using the "rigorous" method of electric field calculation, which consists in the numerical solution of Maxwell's Equations (4)-(7).

According to TB 852, TT load cycles for VSC cables are performed at a voltage U_T=1.85U_0 for a duration of t_T=30 days [6] and consist of 24 "24-h" cycles (12 with negative, then 12 with positive voltage polarity) plus 3 "48-h" cycles with positive voltage polarity. The loss of life fractions for the case study cable during TT load cycles at 5 equally-spaced points in the insulation calculated with the new approach for n_D=10 and n_D=12.5 are reported respectively in Fig. 4 and Fig. 5: with the new approach the fractions of life lost for n_D=12.5 are smaller than those for n_D=10, in line with the improvement of voltage endurance provided by a greater value of life exponent. On the contrary, with the old approach the opposite happened - the relevant Figs. are omitted here for the sake of brevity.

The values of cable life under TT load cycles with the old and new procedure using n_D = 10, 12.5, 15, 17, 26 are reported in Table VII. From Table VII it is evident that, by using the old approach to the IPM-Arrhenius model, all cable lives under TT conditions for n_D=12.5, 15, 17, 26 are well below the life for n_D=10: the greater the life exponent, the smaller are cable lives. And in fact, TT lives for $n_D \geq 15$ are even shorter than the duration of the TT (t_T=30 days): this suggests the TT might not be passed by materials having $n_D \geq 15$, against the well-established experience that the greater n, the better the voltage endurance of cable insulation.

On the contrary, by using the new approach, all cable lives under TT conditions for n_D=10, 12.5, 15, 17, 26 are well above the duration of the TT: the greater the life exponent, the greater the TT lives. This suggests that cable insulations having n_D>10 should pass TT load cycles with no problems - the greater n, the broader the safety margin - in line with the experience on HVDC cable qualification tests, and in general on power cable voltage endurance, which is better for greater values of n. This proves that the new approach to the IPM-Arrhenius model is successful for calculating cable life under load cycles, too.

TABLE VI MAIN DESIGN PARAMETERS OF THE CASE-STUDY CABLE

Parameter	Value
Rated voltage, U_0 [kV]	500
Conductor Material	Copper
Conductor cross-section [mm^2]	2000
Conductor design temperature $T_{cond,max}$ [°C]	70
Insulation Material	DC-XLPE
Insulation thickness [mm]	28.1
Reference electrical conductivity σ_0 [S/m]	10^{-16}
Temperature coefficient of conductivity a [1/°C]	0.084
Field coefficient of conductivity b [mm/kV]	0.0645
Design life L_D [years]	40
Ambient temperature [°C]	20

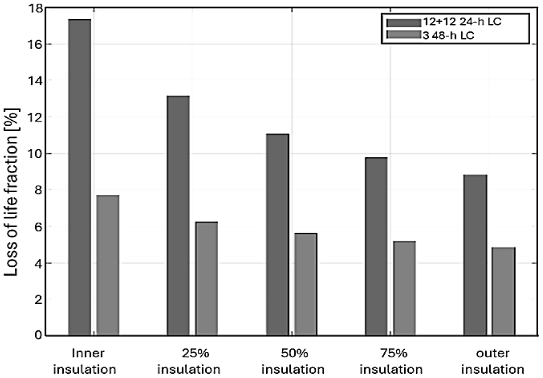

Fig. 4. Life fractions lost by the case-study cable during the TT load cycles for VSC cables at 5 points in the insulation: new approach with n_D=10.

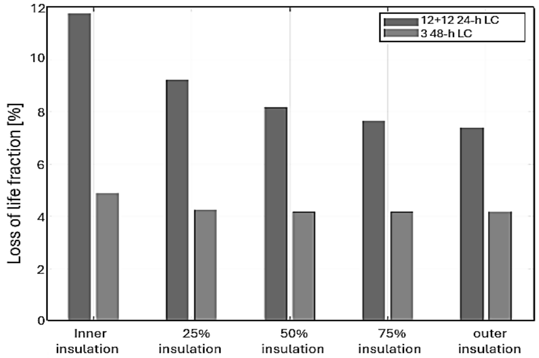

Fig. 5. Life fractions lost by the case-study cable during the TT load cycles for VSC cables at 5 points in the insulation: new approach with n_D=12.5.

TABLE VII CASE-STUDY CABLE LIFE (=LIFE OF THE MOST STRESSED POINT IN THE INSULATION) UNDER TT LOAD CYCLES OBTAINED USING THE OLD APPROACH = $L_{min,OLD}$ AND THE NEW APPROACH = $L_{min,NEW}$

n_D	$L_{min,OLD}$ [days]	$L_{min,NEW}$ [days]
10	124	120
12.5	40	180
15	13	267
17	5	350
26	→ 0	624

VI. DISCUSSION

Voltage and test durations in Tables I-V, as well as life estimates in Figs. 2, 3 and Table VII, are uncertain and must be regarded with care, as they are affected by the main (implicit) hypotheses of both the old approach to the IPM after [6] and - consequently - the new one proposed here, i.e.:

1) test durations in Tables I-V are deemed as conservative estimates of cable system life at the various test voltages;
2) such life estimates (see Figs. 2, 3) rely on the use of the IPM with the related n as representative of the behavior of cable insulation from test down to design voltage. This hypothesis is particularly critical for the estimates of design life, since qualification tests are carried out at voltages significantly greater than design voltage;

3) the IPM for the cable is deemed as representative of the whole cable system behavior. This is a consequence of the emphasis put by Appendix A of [6] on the main role played by cables in qualification load cycles, but of course accessories are fundamental for cable system performance and their behavior needs to be assessed by ad hoc tests in addition to qualification load cycles [6].

VII. CONCLUSIONS

Resorting to the relevant theoretical-empirical background, the paper has shown the limits of the current approach to the IPM followed in Cigrè TB 852 for the selection of qualification load cycle test voltages. From these limits a new approach has been proposed, based on the evidence that qualification tests are successfully passed by well-designed, manufactured and installed cable systems, and that new cable insulations with greater life exponent *n* have improved voltage endurance.

Following the new approach, some new sets of qualification test voltages have been suggested that depend on the declared value of life exponent *n*. Such suggestion implies that, if a cable system passes qualification load cycles, this not only demonstrates satisfactory behavior under the time-varying electro-thermal-mechanical stress produced by qualification load cycle voltages and durations, but also that cable insulation possesses the declared value of *n*. This proves the satisfactory long-term voltage endurance properties of cable insulation associated with that declared value of *n*, which otherwise can be only assessed in laboratory tests on much smaller specimens.

In the paper the new approach has also been applied to the IPM-Arrhenius model used in the life estimation procedure for HVDC cables under qualification load cycles. The paper has reported an illustrative example of the application of the procedure with the new IPM-Arrhenius model to a 500 kV VSC DC-XLPE insulated cable subject to TT load cycles. The results show the satisfactory behavior of the new approach, as they are in line with the two above-cited empirical outcomes: 1) qualification load cycles are passed by good cables; 2) the greater the life exponent, the better the cable voltage endurance.

For these reasons this new approach might be useful for internal R&D tests of manufacturers on cable loop prototypes, as well as for future issues of Cigrè TB 852 and IEC 62895.

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