A.1.2. Extension des câbles à isolation polyéthylène réticulé au niveau 500 kV sur la base des progrès obtenus sur la technologie

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A.1.2. Extension of XLPE cables to 500 kV based on progress in technology

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Résumé

L'évaluation des résultats d'essais récemment obtenus sur des câbles HT isolés au PR a permis de réaliser, au niveau de 500 kV, la même épaisseur d'isolant qu'avec 400 kV il y a quelques ans. Cela a été rendu possible grâce aux progrès achevés dans le domaine des matières premières et des techniques de fabrication ayant mené à des caractéristiques électriques plus homogènes. Cela est vrai surtout pour la tenue au claquage pendant des essais aux ondes de choc et à tension alternative. On a constaté que la limite inférieure de la rigidité diélelectrique (choc) était nettement plus élevée, et l'évaluation des essais récents de longue durée sous tension alternative justifie la conclusion que, à condition d'absence d'eau, le vieillissement est practiquement nul. Des câbles 500 kV ayant une épaisseur d'isolant de 30 mm, ce qui correspond à un gradient maximum de 15,5 kV/mm, ont été soumis à premières essais de type, et ils satisfont à toutes les exigences publiées ou spécifiées dans quelques normes nationales.

Abstract

The evaluation of latest test results on XLPE high voltage cables leads to the same insulation thickness for 500 kV as it did a few years ago for 400 kV. The reason is given by progresses in material and production technologies resulting in more homogeneous electrical properties of the present cables as compared to the former ones. This holds true above all for the breakdown behaviour under impulse and under ac test conditions. There has been noticed a marked increase of the lower breakdown strength limit (impulse), and the evaluation of recent long term tests at ac voltage and load cycles justifies the conclusion that there seems to be no electrical ageing, provided that water is excluded. 500 kV cables with an insulation thickness of 30 mm corresponding to a maximum operating gradient of 15.5 kV/mm have been successfully subjected to first type tests, and they fulfill any safety requirements as published in the literature or specified by some national standards.

Introduction

In spite of worldwide intensive research and development activities, up to now the only service experience with XLPE-insulated power cables for the rated voltage 500 kV is based on a few short links without joints [1]. Larger systems with joints have not yet been installed to commercial networks. There are three main reasons for this fact:

- the necessarily high operating gradients of EHV cables leading to corresponding electrical stresses not only within the cable insulation but also at the interface with the accessories
- the long-term properties of thick-walled XLPE dielectrics under high stress conditions which are not yet cleared up beyond all doubt and
- the lack of appropriate accessories, especially of joints which should easily be assembled and free of maintenance.

The only extended power cable system above 275 kV with solid polymeric dielectrics is operated in France [2]. The insulation of these cables, however, consists of non-crosslinked low density polyethylene (LDPE) which is accepted only by a few utilities due to its limited operating temperature. Therefore most of the manufacturers concentrate on the development of XLPE power cables for 400 to 500 kV.

Since it has been recognized that a standardization of insulation thicknesses was not advisable in the fields of HV and EHV cables, each manufacturer has to dimension new EHV XLPE cables according to their own philosophy. Only EdF specified the tolerable electric stresses within the insulation of polymeric cables which can be treated as rough criteria concerning the wall thickness of the present French 400 kV LDPE cables [3]. Comparable limits are part of the more general new French Standard C 33-253 (draft) for polymer-insulated cables including XLPE above 150 kV up to 500 kV [4]. In Japan the most important cable manufacturers and big utilities have agreed on common design methods which are applied to all XLPE HV and EHV cables [5].

Some years ago, the authors of the present paper developed a modified design procedure and calculated the wall thickness of prototype XLPE cables for 400 kV based on former test results to be 31 mm [6]. In the meantime many km of HV and EHV XLPE cables have been manufactured and successfully tested, additional research work was carried out increasing the know-how and experience so that today the step to the next voltage level can be performed, i.e. 500 kV.

Calculation of insulation thickness

Procedures and definitions

The thickness of the just-mentioned 400 kV XLPE cables [6] had been calculated by the application of four independent design methods roughly described by the following keywords:

- the mean ac field strength to be withstood for the duration of one hour (method A),
- the average lightning impulse field strength to be resisted (method B),
- the maximum impulse withstand field strength at the conductor (method C),
- the maximally admissible ac field strengths at the inner and outer semiconductive layers and a limited breakdown

probability of extended cable systems under operating conditions (method D).

Procedures A to C are directly used at dimensioning the new XLPE cables for 500 kV, whereas the stress limits given by method D will be checked subsequently.

Applying methods A and B at calculating the insulation thickness w gives an equation of the type

$$w = U_d \, / \, E_d \qquad (1a)$$

which is in case of method C extended to relation 1b:

$$w = U_d \, / \, (E_d \cdot \eta). \qquad (1b)$$

U_d and E_d mean the so-called design voltages and field strengths, respectively, and η is the Schwaiger factor, i.e. the quotient of the average and the maximum electric stress within a given electrode arrangement.

The voltages U_d mainly depend on the service conditions of the cables to be developed. Considering method A, $U_d = U_{dac}$ is an ac voltage derived from the operating one by means of equation 2:

$$U_{dac} = U_0 \cdot k_T \cdot k_o \cdot k_t \qquad (2)$$

with U_0 = 290 kV for the rated voltage U_N = 500 kV, k_T = 1.25 as the temperature factor, and k_o = 1.15, the overvoltage factor. Finally k_t, the ageing factor, is transforming the operating voltage U_0 to be withstood over the proposed service life of the cable (40 years) to a fictive one hour test voltage. For this purpose one has to apply the so-called life law $U^N \cdot t$ = const. leading to:

$$k_t = (40a \, / \, 1h)^{1/N} = (350400)^{1/N}. \qquad (2a)$$

Thus k_t depends on the life exponent N describing the ageing behaviour of the cable insulation concerned; it will therefore be taken up later together with other dielectric properties.

The design voltage U_{di} under impulse conditions (methods B and C) is connected with the standardized basic impulse level (BIL) of the respective nominal voltage by three correction factors (equ. 3):

$$U_{di} = BIL \cdot k_T \cdot k_f \cdot k_s \qquad (3)$$

with BIL = 1550 kV for 500 kV cables according to IEC Specification 71-1, k_T = 1.25 as the temperature factor from above and $k_f = k_s$ = 1.1 each, meaning the repetition and safety factors, respectively. The design field strengths E_d are withstand values of the intended cable insulation under specified test conditions. They must be substantiated by the manufacturer in an appropriate manner (refer to the following chapters).

Dielectric properties of XLPE insulations

AC breakdown strength and ageing behaviour

Test objects for determining the design stresses should as far as possible consist of actual HV and EHV XLPE cable insulations. However, there may occur the problem that breakdown tests on good quality power cables do not reveal expressive results. In many cases the only information of such tests consists of the conclusion that the investigated property is „better than...“ (a given limit).

As an example for this statement, *figure 1* shows the results of ac voltage life tests on HV XLPE cable lengths at ambient temperature, evaluated in a double-logarithmic diagram. With the exception of very few samples – stemming from the very beginning of the manufacturing period about 15 years ago – no long-term breakdown at all took place. Nevertheless one can conclude from this plot that the electric strength E_{dac} after 1h under stress is better than 30 kV/mm, and the life exponent N in any case exceeds the limit of 12. In addition, the computed 50%-breakdown strength after 1h for later safety controls according to method D amounts to 42.3 kV/mm. However, the actual value of N, necessary to calculate the ageing factor k_t in equation 2, cannot be obtained from the results in figure 1; other methods must be applied.

Taking into consideration that the life law means a mathematical approach to describe the physical effect of life consumption opens possibilities for an indirect estimation of the life exponent N. If ageing takes place at all, it should affect not only the long-term breakdown strength but also other dielectric properties. To check this statement, XLPE power cables with 5.5 mm thick insulation were aged for 1 to 6 years under moderately increased ac voltages and elevated temperatures and subsequently subjected to an ac short time break-

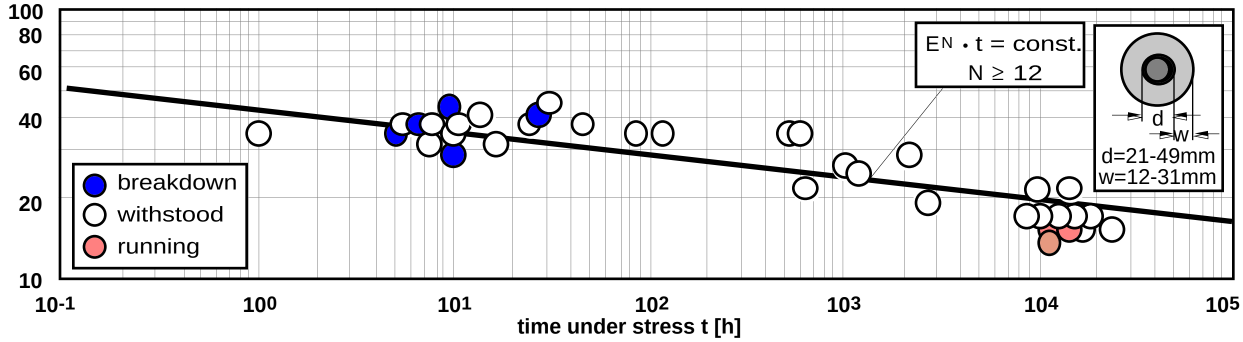

Figure 1: ac voltage life tests on HV and EHV XLPE cable lengths (l = 100 m) at ambient temperature.

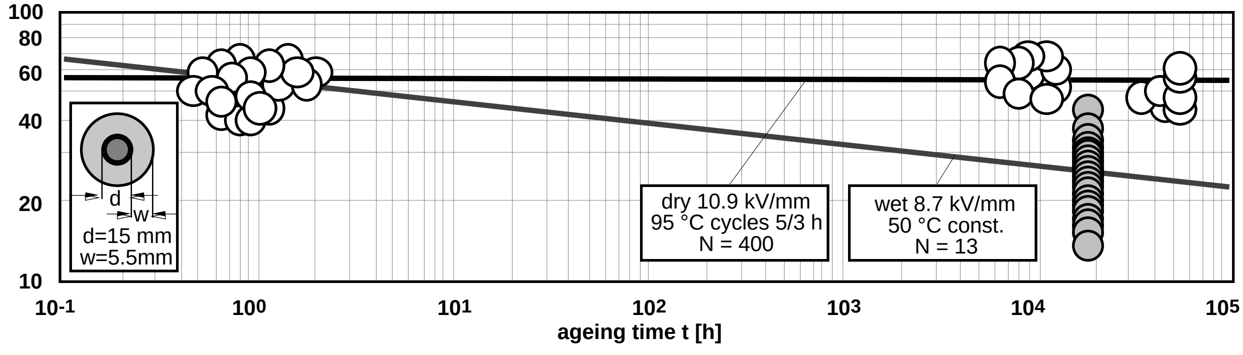

Figure 2: ac voltage ageing tests on 20 kV XLPE cable lengths (l = 15 m). Evaluation by short time ac step tests until breakdown.

down step test. As additionally accelerating ageing conditions, some of the cable samples were directly contacted with water in the stranded conductor and at the screen*). The results of these experiments are plotted in *figure 2*; they lead to the following conclusions:

- the assumption that ageing erodes several insulation properties obviously holds true, as one can see from the distinctly reduced short time breakdown strength of the wet-aged samples. The related life line, automatically computed by the least square method, exhibits a life exponent N = 13
- without water contact there seems to occur no ageing at all. Although subjected to higher stress and temperatures as compared with the water-aged cables and test durations up to almost six (instead of two) years, the life curve of the dry samples corresponds to an exponent N approaching the value „infinite“ (formally calculated as above, it amounts to N = 400).

This finding, up to now based on 17 long-term cable tests, is in good accordance with experimental results recently published by Dorison et. al. [7]. Evaluating several properties including breakdown behaviour of XLPE cable insulations after electrical and thermal long duration stressing the authors report the same observation as just mentioned, i.e. ageing is not evident – at least, as far as the field strength keeps below 27 kV/mm (accordingly, Cigré WG 21-03 recommended to limit the conductor stress at routine tests on delivery lengths to this value [8]). Nevertheless, for the time being it would mean a premature conclusion to neglect any electric ageing effects in XLPE dielectrics. However, the new results justify in any case the assumption of a life exponent N = 17 for further cable designing. The same value has been elaborated by Japanese engineers for the application to their own development of future 500 kV XLPE cables [1]. So the missing quantities to calculate the insulation thickness by means of method A from above are now available: E_{dac} = 30 kV/mm (ref. to fig. 1) and N = 17.

Impulse breakdown strength

Following internal quality specifications, XLPE cable samples are periodically taken from the running high voltage production and subjected to lightning impulse tests at ambient temperature until breakdown. This measure of quality assurance had been started at the very beginning of the HV manufacture. Therefore several hundred results are now available providing a safe statistical basis to evaluate the belonging insulation properties and to determine the necessary quantities for designing future cables.

Figure 3 shows the Weibull plots of the impulse breakdown tests on HV and EHV cables performed during the recent five years. The two distributions in this diagram represent the average and the maximum breakdown strengths, respectively. With respect to the calculation of insulation thickness for 500 kV by means of methods B and C, fig. 3 contains the mean design field strength under impulse conditions, E_{dimean}, and its corresponding max. value at the conductor, E_{dimax}. They amount to 80 kV/mm and 125 kV/mm, respectively. Furthermore, one can read the slopes b of the Weibull distributions to be between 14 and 15. For safety reasons, however, only b = 12 will be applied to the volume transformation later on.

Table 1 summarizes once more the design quantities as explored by experiment.

Cable dimensions

Inserting the values of table 1 into equations 1 through 3 results in different insulation thicknesses of 500 kV XLPE cables, dependent on which method is applied:

method A:

$$w(A) = U_{dac}/E_{dac} = 290 \cdot 1.25 \cdot 1.15 \cdot 2.12 / 30 = 29.4 \text{ mm} \qquad (4)$$

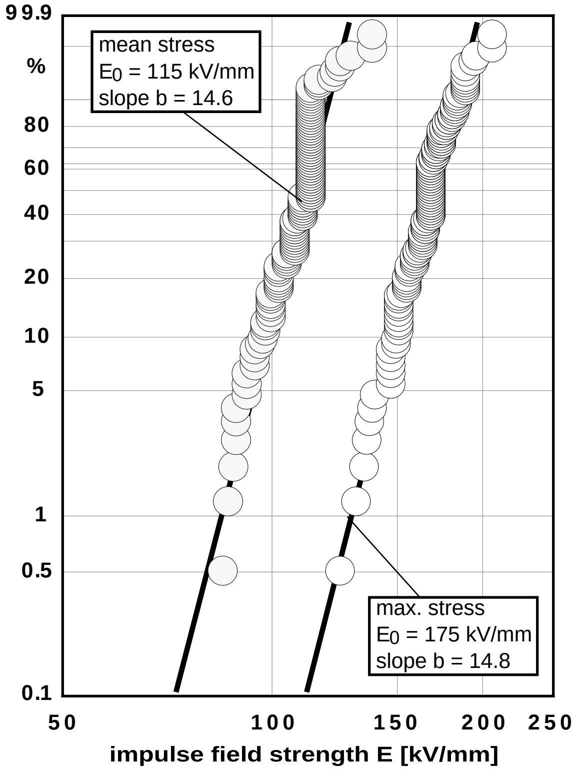

Figure 3: Impulse breakdown strength of HV and EHV XLPE cables from the running production.

Method	Design parameters
A	life exponent N = 17 ac withstand strength (1h) E_{dac} = 30 kV/mm
B	mean impulse strength E_{dimean} = 80 kV/mm
C	max. impulse strength E_{dimax} = 125 kV/mm
D	life exponent N = 17 ac breakdown strength (1h) E_b = 42.3 kV/mm Weibull slope b = 12

Table 1

method B:

$$w(B) = U_{di}/E_{dimean} = 1550 \cdot 1.25 \cdot 1.1 \cdot 1.1 / 80 = 29.3 \text{ mm} \qquad (5)$$

method C:

$$w(C) = U_{di}/(E_{dimax} \cdot \eta) = 2345/(125 \cdot \eta) = f(\text{conductor size}). \qquad (6)$$

Since the insulation thickness should comply with each of the design methods considered, the actual cable dimensions are determined by the largest of these values. Methods A and B reveal almost the same wall thickness which must be compared with the conductor-dependent solution of method C. In the cylindrical arrangement of a single core cable the homogeneity factor $\eta = E_{mean} / E_{max}$ is given by equation 7:

$$\eta = \{r \cdot \ln(R / r)\} / w = \{r \cdot \ln[(r + w) / r]\} / w \qquad (7)$$

with R and r meaning the outer and inner radii of the insulation layer. Entering equ. 7 into equ. 6 leads after some modifications to an exponential expression for w(C) as a function of radius r which depends on the conductor size:

$$w(C) = r \cdot \{\exp[U_{di} / (r \cdot E_{dimax})] - 1\}. \qquad (8)$$

Figure 4 contains the results of the three wall thicknesses plotted versus conductor size from 630 mm^2, the smallest conductor considered for 500 kV up to the largest one, 2500 mm^2. One can see that for all conductors including and beyond 1000 mm^2 a thickness of 30 mm is an appropriate dimension for the insulation of future 500 kV XLPE cables. Only cables with small conductors below 1000 mm^2 require thicker insulations to avoid critical field enhancements at the conductor shield.

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*) The ageing procedure applied here corresponds to the so-called Extended Type Test according to VDE 0273.

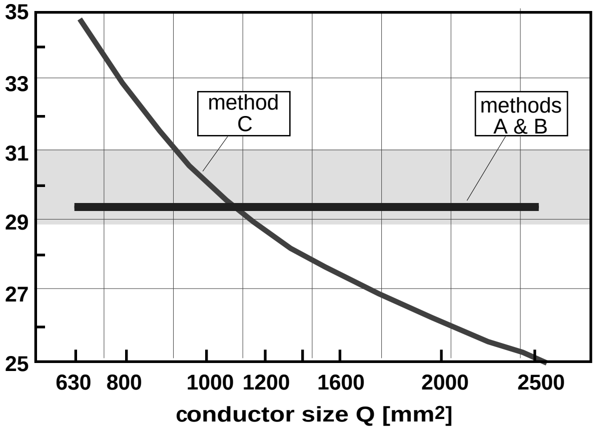

Figure 4: Resulting insulation thickness of 500 kV XLPE cables according to different design methods.

Stress control by means of method D

The new French Standard C 33-253 [4] specifies two essentials with respect to XLPE cables for rated voltages above 150 kV under operating conditions:

- the field strengths at the conductor and at the core surface are limited to 16 kV/mm and 7 kV/mm, respectively, and
- the statistical fault probability within a three phase cable system of 100 km total length shall be ≤ 20% per year.

To check the first-mentioned stress conditions, equation 9 describing the field distribution in the cylindrical insulation must be solved for the respective worst case, i.e. for the smallest conductor considered at calculating the conductor stress and for the biggest one at determination of the surface field:

$$E(x) = U_0 / [x \cdot \ln(R / r)]. \quad (9)$$

Assuming the dimensions for 630 mm^2 as smallest conductor, 2500 mm^2 as the biggest one and the wall thicknesses according to figure 3, equ. 9 leads to 15.5 kV/mm at the conductor and almost exactly 7 kV/mm at the surface, respectively. This means, the field limiting conditions according to the French Standard 33-253 are fulfilled.

Checking the fault limiting condition of this specification requires some statistical calculations which had elaborately been described by the authors in their former paper [6]. Accordingly the fault prognosis can be performed in three steps:

1. converting the 1h breakdown strength E_b from table 1 to the corresponding value after 1 year. This time transformation succeeds by the application of equation 2a in a modified manner:

$$E_b(1a) = E_b(1h) \cdot (1h/1a)^{1/N} \quad (2b)$$

2. calculating the electric strength after 1 year corresponding to the breakdown probability p_1=20% from the just obtained strength at p_2=50% (probability transformation):

$$E(p_1) = E(p_2) \cdot \exp\{[\ln(-\ln(1-p_1)) - \ln(-\ln(1-p_2))] / b\} \quad (10)$$

3. converting the result of equation 10 which is valid for the laboratory test samples from figure 1 with an insulation volume V_t (0.22 m^3 on average) to the desired 20% breakdown strength of the 100 km three phase cable system with its total volume V_0 (volume transformation):

$$E(V_0) = E(V_t) \cdot (V_t / V_0)^{1/b}. \quad (11)$$

Using the test results of table 1, line “method D”, one obtains an area of admissible stresses which depends on the volume (i.e. insulation thickness and conductor size) of the 500 kV cable system to be designed. In any case this admissible stress must be larger than the mean operating gradient which is given by the quotient of service voltage U_0 and wall thickness w.

Figure 5 shows the results as a function of w. One can see that 500 kV cables with the thickness w = 30 mm from above fulfill the reliability condition of the specification [4] for the entire area of conductor cross sections in a safe manner.

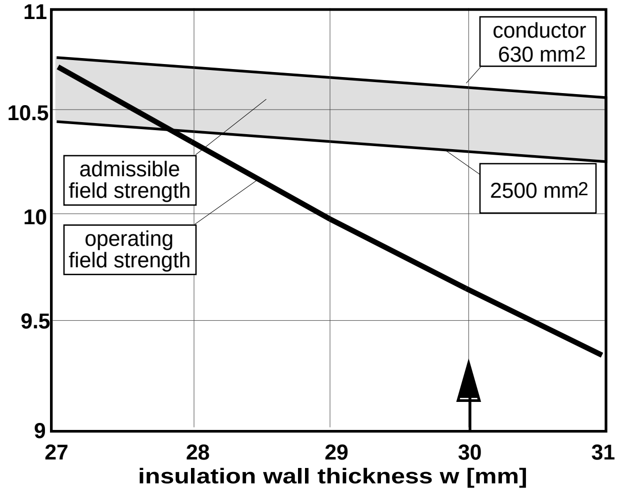

Figure 5: Admissible field strength of 500 kV XLPE cables according to the breakdown probability p≤20% p.a. in a three phase system of 100 km.

Type tests on full-sized cables

Using a horizontal production line, first prototype XLPE cables with 1200 mm^2 Milliken conductor for 290/500 kV were manufactured for experimental investigations. Short lengths of these cables were successfully subjected to development tests with ac and with lightning impulse voltages the results of which being entered in figures 1 and 3, respectively. After material inspections and check of mechanical properties, a complete type test (electrical properties) was carried out. Due to the lack of binding standards its details were selected according to the recommendations of Cigré WG 21-03 [8] and of specifications taken from IEC Publication 840 and VDE Standard 0263.

The test setup consisted of the cable with two outdoor terminations and a so-called back-to-back joint made of two SF_6 switchgear sealing ends (see *figure 6*). The field control within

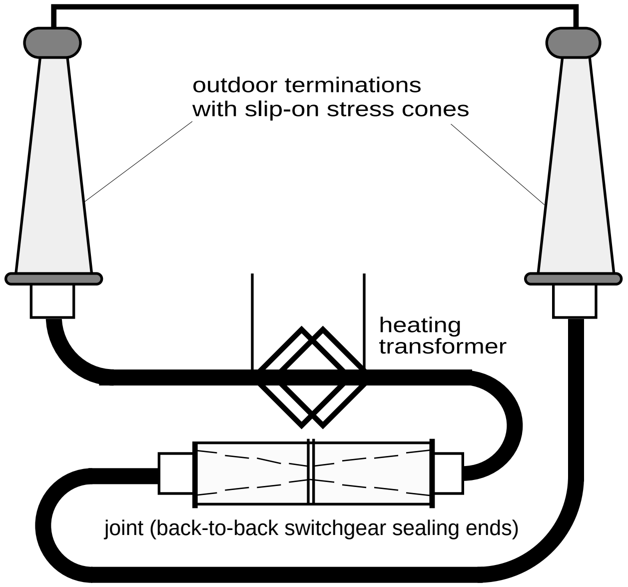

Figure 6: Principle setup for type testing on the 500 kV XLPE cable.

test	procedures and requirements	result
bending test	diameter 20 • (D+d) ± 5 %: 3 cycles	passed
pd test #1	1.5 U_0 = 435 kV: pd charge Q < 5 pC	passed
tan δ measurement	U_0 = 290 kV, ϑ = 95 °C: tan δ < 10 • 10^{-4} (separate cable)	passed
heating cycle voltage test	2 U_0 = 580 kV, 20 load cycles 8/16 h up to ϑ = 95 °C: no breakdown (bd)	passed
pd test #2	1.5 U_0 = 435 kV: pd charge Q < 5 pC	passed
impulse volt. withstand test	1550 kV, 20 °C and 100 °C, 10 pos. and neg. impulses each: no bd	passed
ac volt. test	2 U_0 = 580 kV, 20 °C, 15 min: no bd	passed

Table 2

the accessories was realized by means of prefabricated silicone rubber stress cones. The tests performed and its results are summarized in *table 2*. All tests were passed successfully.

Discussion and perspectives

Just five years after calculating the insulation thickness of 400 kV XLPE cables with the result of 30...31 mm [6], the application of identical design criteria and safety margins exhibits today the same dimensions for the rated voltage 500 kV. As the methods have not changed this surprising accordance must be due to improved design quantities. Indeed, as demonstrated by the comparison of the respective properties in *table 3* most of the present values are exceeding the former ones.

	E_{dac} kV/mm	E_{dimean} kV/mm	E_{dimax} kV/mm	b	N
1995	30	80	125	12	17
1990 [5]	30	70	115	10	12

Table 3

To explain this finding from the physical point of view, one has to distinguish between impulse and ac test results. The essential change under ac conditions, the increase of the life exponent N from 12 to 17, rests on the conclusion that there is almost no electrical ageing at moderately enhanced stress, or if it happens yet, the degradation of the dielectric properties occurs much slower than usually assumed. This statement, based on the results in figure 2, is not an invention of the present contribution. For example, more than ten years ago Bahder [9] drew the conclusion from tests on XLPE and EPR insulated cables that no ageing at all takes place as far as the field strength is limited to a threshold value of 10...15 kV/mm. Therefore the application of N=17 to the statistical voltage-time transformations is in any case justified.

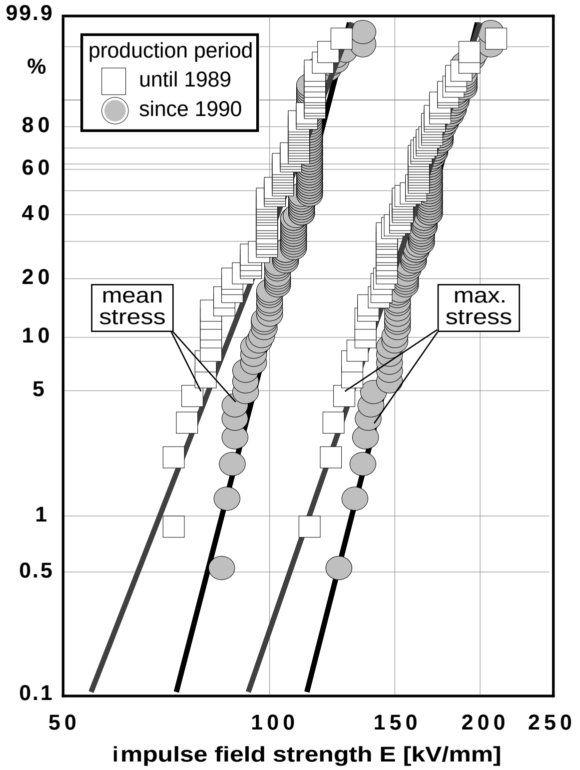

Figure 7: Impulse breakdown strength of HV and EHV XLPE cables from different production periods.

With respect to impulse breakdown a distinct quality increase can be substantiated which caused the improvement of the belonging design quantities during the recent years. As a demonstration for this statement, *figure 7* contains a comparison of impulse test results on HV XLPE cables from the running production before and after 1989. The former results comprised the experimental basis of the thickness calculations for 400 kV cables in [6] and had been published there, whereas the younger distributions are originally taken from figure 3 of the present paper. Obviously, the actual results represent the more even behaviour, exhibited by the larger Weibull slope amounting to 14...15 instead of 10...11. This observation is especially due to the absence of the lowest breakdown values as compared with the former distributions.

The last-mentioned fact demonstrates the effect of better purity of the insulation and semiconductive shields and – above all – of a distinctly increased homogeneity of the interfaces between these layers. Thus a consistent quality control system starting on-site at the supplier of the raw materials in combination with improved methods of material handling in the cable factory and with various efforts to optimize the manufacturing processes have resulted in a measurable progress in technology. Further steps are initiated, e.g. the changeover of the entire production to clean room conditions class 1000 for additional safety.

Consequently the insulation thickness of future 400 kV XLPE cables can be reduced as well. Applying the same design methods and criteria as described above leads to an insulation wall of 27 mm instead of 31 mm.

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