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Insulated Cables for Energy Transmission at UHVAC Level

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SUMMARY

Experimental UHV Overhead Lines have been already installed in several places worldwide. Most likely, public acceptance of Overhead Lines will be become more challenging and will be subjected to the possibility of undergrounding in some areas like river or fjords crossings or sensitive landscape places. It is therefore very important to also have UHV underground solutions available.
UHV lapped insulated cables have been offered for more than 20 years with fully tested solutions. Several publications describe the possibilities given by SCFF cable systems.
Extruded cables, now preferred for land applications, have been used at voltages up to 500kV for more than 20 years and they have had excellent service records. A new survey regarding worldwide service experience will be conducted by WG B1.55 recently approved by Cigre TC.
The successful experience of EHV cable systems is mainly due to a stringent qualification process as specified in Cigre recommendations and IEC Standard 62067. Following the advice of CIGRE SCB1, a long term accelerated ageing test at 1.7 U_o (for 1 year) was introduced in the relevant IEC cable Standard in order to gain some indication of the long term reliability of a cable system. This test, known as the "prequalification test", or "PQ test" is to be performed on the complete system comprising the cable, joints and terminations in order to demonstrate the long term performance of the system.
These recommendations and standards are based on the consideration of the Electrical Field in the insulation of cables and accessories and at the interface between them. Values for Electrical Fields of 16 kV/mm in the cable insulation and 8 kV/mm at the interface between cable and accessories are currently used at 400/500 kV levels. Long term tests on XLPE cables have been carried out on extruded cables .From these tests, it can be concluded that 800 kV extruded Cable Systems can be made available soon with a BIL of approximately 1800 kVp to 2100 kV. The paper will detail all these points regarding UHVAC and will also briefly address UHVDC issues. Of course, new Cigre Recommendations for testing such cables are necessary and will be shortly included in the work program of SC B1. In the meantime, and even for higher UHVAC levels, SCFF are available.

KEYWORDS

Insulated Cables; SC B1; UHVAC; Electrical Stress; Extruded Cables; SCFF

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1. Introduction

Insulated cables for 110 kV and higher system voltages have been used since the 1920's with oil-impregnated paper as insulation. By the introduction of oil at a positive pressure as impregnant for the paper-insulation of the cable, void formation in the insulation (between paper layers, in butt spaces etc.) was eliminated. The impregnant was maintained inside the cable with a metal sheath. The improvements of design, materials, manufacturing techniques etc. made an increase of the rated voltage for the oil-filled paper-insulated cables possible. In the 1950's the first oil-filled paper insulated cables were installed in a 380 kV network. Later on, EHV then UHV lapped insulated cables have been offered for more than 20 years with fully tested solutions. Several reports on such SCFF cable systems have been published [1][2] in CIGRE Events.

During the 1950's the technology of extruded insulation was introduced for medium voltage cables. The first high voltage cables with extruded insulation on 110kV systems were installed in the 1960's and on 225 kV systems in late sixties The improvements of design, materials, manufacturing techniques etc. resulted in cables with extruded insulation for even higher voltages. Today cables with extruded insulation have been used for more than 25 years at installations at system voltages up to 500 kV [3][4]
Very soon, cables with extruded insulation ("extruded cables") were found to have good impulse voltage strength. With the introduction of medium and high voltage extruded cables, the expected lifetime of these new technology cables was questioned. Very early focus was concentrated on methods for determining the expected lifetime of cables with extruded insulation.

A number of accelerating ageing tests were started at the manufacturers'plants and at test institutions around the world for establishing the ageing parameters. Different statistical methods were used for finding a model to evaluate the estimated lifetime from the test results. The Weibull distribution became the world-wide used method to estimate the expected lifetime for a full-scale cable based on the results of ageing tests on model cables. Theoretical methods for correction of length, insulation volume (diameter, thickness), temperatures, threshold stresses etc. were introduced [5]

The results from the ageing tests combined with the experience from medium voltage cables in service were used for designing cables at higher rated voltages. In the beginning of 1970's 132 kV cables with extruded insulation were installed. Further improvements in design, materials and processes made it possible to increase the design stresses for the high voltage cables, which was necessary for the increase of the rated voltage to 220 and 400 kV.

In a Workshop organized by Jicable in 1987 [6], it was confirmed by 80 experts coming from 12 countries worldwide that the ageing of the extruded insulation was the main criterium to take into account in the design of extruded cables. At this time, it was already stated that a rated voltage of 800 kV could be envisaged with increased Working Gradients. In 1991, WG 21.09 from SC 21 (now SCB1) published a report in Electra 139 titled "*Working Gradient of HV and EHV Cables with Extruded Insulation and its Effect*" [7] followed by a report from WG 21.04 published in Electra 169 in December 1996 "*Criteria for Electrical Sress Design of HV Cables*" [8] and Technical Brochure 189 "Insulation Co-Ordination for HVAC Underground Cable Systems" by JWG 21/33 in June 2001[9]

The successful experience of EHV extruded cable systems is mainly due to a stringent qualification process as specified in Cigre recommendations (WG 21.03 in Electra 151/December 1993/TF 21.18 in Electra 193/December 2000 and WG B1.06 in TB 303/August 2006)[10][11][12][13] and IEC Standard 62067[12]. On the advice of CIGRE SCB1, a long term accelerated ageing test at 1.7 U_o for approximately 1 year was introduced in the first edition of the relevant IEC cable Standard (and maintained in the following edition), in order to gain some indication of the long term reliability of a cable system. This test, known as the "prequalification test", was to be performed on the complete system comprising the cable, joints and terminations in order to demonstrate the long term performance of the system. The range of approval for the tests is highly depending on the Electrical Stress within the Cable and the accessories.

2. Electrical Field

Before going to next sections, it is important to understand what is the electrical stress within the cable insulation and at the interface of the cable and accessories (joints and terminations).
In the case of a radial field, equipotential lines are cylindrical and concentric to the conductor and the electrical stress at a distance r from the axis is:

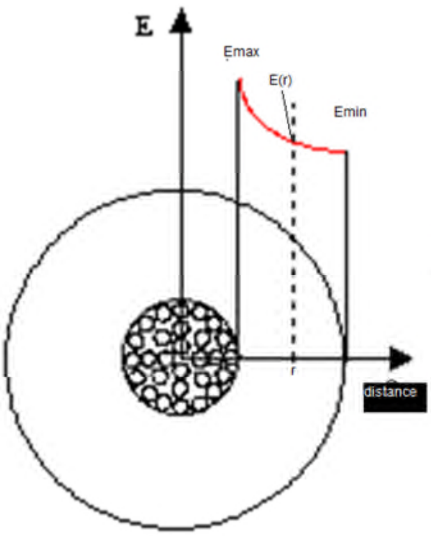
$$Er = \frac{.U_0}{r.\ln\left(\frac{\mathrm{Re}}{\mathrm{Ri}}\right)} kV/mm$$

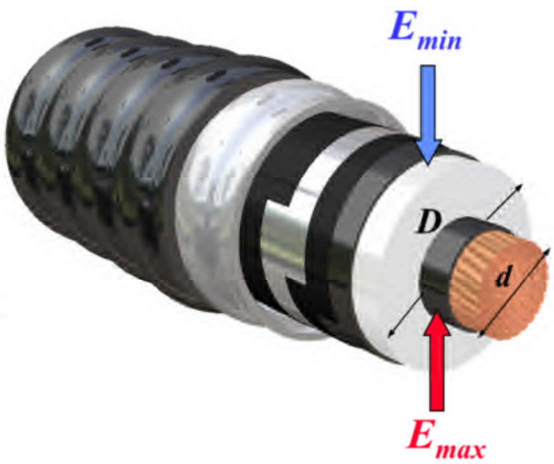
where: Ri and Re are the internal and external radii of insulation,
If D=2Re is the diameter over the Insulation

and d=2Ri is the diameter over the conductor or the semicon layer.

The stress is maximal $\boldsymbol{E_{max}}$ on the conductor (or the inner semi-con layer) where r=Ri and minimal $\boldsymbol{E_{min}}$ at the surface of the insulation layer where r= Re

$$E_{\max} = \frac{2.U_0}{d.\ln\left(\frac{D}{d}\right)} ....kV/mm$$ and $$E_{\min} = \frac{2.U_0}{D.\ln\left(\frac{D}{d}\right)} ....kV/mm$$





$\boldsymbol{E_{max}}$ is very important for the ageing of the insulation and the performance of the cable under impulse.
$\boldsymbol{E_{min}}$ is critical for the compatibility of the cable and the associated accessories (joints and terminations)

3. Ageing of cable insulation: state of the art as described in CIGRE TB 189 [9]

The electrical performance of cable insulation generally decreases with time due to degradation processes of the insulating materials. The mechanisms of the ageing process are different depending on the physical properties of the materials used for the insulation.

The ageing of cables with lapped impregnated insulation is mainly influenced by the operating temperature. Gas production in the insulation due to thermal degradation is the dominating ageing process for this cable type. As long as the gas can be dissolved in the impregnating liquid, the electric withstand stress remains nearly constant. The applied AC stress does not have a significant influence on the ageing, provided that it is held below the PD inception stress. Therefore, in such cables, the effect of electric ageing is negligible.

The ageing process of cables with extruded insulation is significantly influenced by the applied electrical stress. Assuming, that the physical process responsible for the ageing does not change, the time to breakdown for a given stress as well as the breakdown stress for a certain time are stochastic values which are represented by homogeneous distribution functions. The results of many tests have shown that both values may be approximated by Weibull distributions with two parameters (scale parameters at 63 % probability t_0 and E_0, Weibull slopes a and b, see Figure 1)

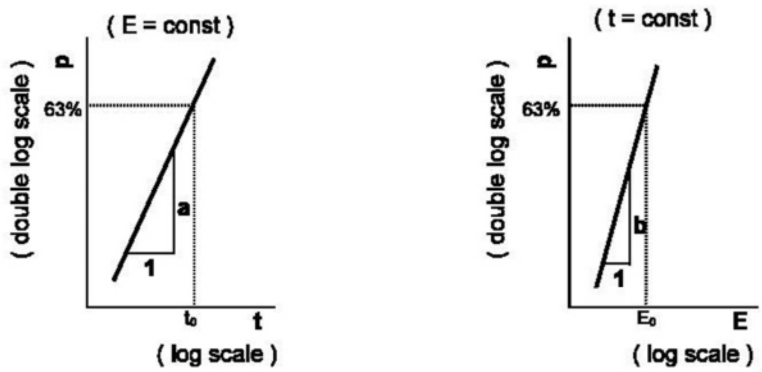


Fig 1: Partial Weibull distributions of breakdown time (constant stress) and stress (constant time) for an extruded cable insulation

According to this mathematical model the breakdown probability as a function of time for a given cable at constant electrical stress is: $p(t) = 1 - \exp(-(t/t_o)^a)$

For the same cable the breakdown probability as a function of the electrical stress applied for a constant time can be written as: $p(E) = 1 - \exp\left(-(E/E_o)^b\right)$

The two distribution functions may be combined, so that the complete equation for the breakdown probability of a given cable sample is

$$p(t,E) = 1 - \exp\left(-(t/t_o)^a (E/E_o)^b\right)$$

For a constant breakdown probability the following relation may be derived from the above:

$$\left(\frac{t}{t_o}\right)^a \cdot \left(\frac{E}{E_o}\right)^b = \text{const}$$

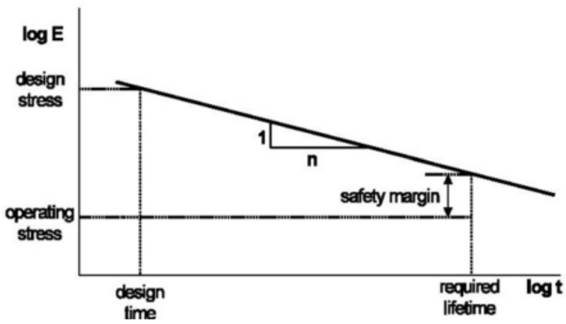
Introducing the lifetime exponent n as the quotient of the Weibull slopes b and a

$$n = \frac{b}{a}$$

the lifetime law for an extruded cable insulation becomes finally.

$$E^n . t = const$$

Published values of the lifetime exponent n for XLPE cover the range from 12 to 20. According to the lifetime law for extruded cable insulation, high electrical stress applied for short time causes the same ageing as lower stress applied for a longer duration, provided that all other operating conditions remain unchanged. The design philosophy for extruded cables must consider this effect. Basic values of the design stresses are usually derived from short-term tests (design stress/ design time in Figure 2). Considering the ageing effect it has to be ensured that, at the required lifetime, there is a sufficient safety margin left to cover accelerated ageing effects due to temporary overvoltages, surges etc.
The different ageing behavior of cables with lapped impregnated insulation and extruded insulation is also the reason for the different design and testing philosophies according to the relevant standards and recommendations. Typical differences in lifetime curves for lapped and extruded cable insulation are shown qualitatively in Figure 3



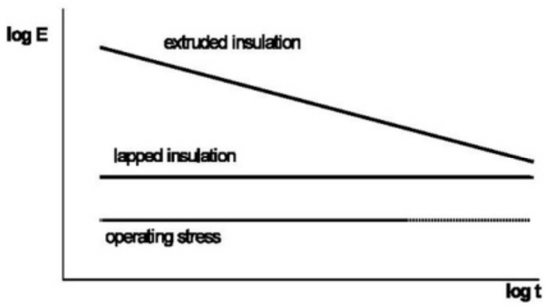


Fig 2 Lifetime curve for extruded cable insulation **Fig 3 Qualitative lifetime curves for cables under electric stress**

4 Basic Design Practices for Insulated Cables as described in CIGRE TB 189 [9]

4.1 Basic insulation design of high voltage AC cables with lapped insulation

The insulation of such cables is formed by a number of thin paper tapes wounded around the conductor. The shape of the conductor is circular, except for external gas pressure cables, where an oval shaped conductor is used. Depending on the type of cable the insulation is impregnated with low viscosity oil or with a non-draining high viscosity insulating mass.

The surface of the conductor is more or less irregular due to the interstices between the single wires. To avoid electrical stress concentrations at such irregularities several layers of semi-conductive carbon black paper tapes are applied on the conductor surface. For high voltage cables it is essential to form a pure radial electric field inside the insulation. Therefore semi-conductive carbon black paper tapes, normally in combination with metal coated paper tapes are used also over the insulation.

In order to achieve a satisfactory long duration AC withstand characteristic, it is necessary to avoid ionisation inside the insulation. Ionisation can take place in gas filled voids, which could be formed in the insulation by different rates of expansion and contraction of the cable components during load cycles. Several cable types have been developed using different mechanisms to overcome the ionisation problem and to form so-called thermally stable cables.

a) Low pressure oil filled cable with paper insulation

The paper insulation of low pressure oil filled cables is impregnated with low viscosity insulating oil. During the heating phase of a load cycle the expanding oil can flow through longitudinal channels inside the conductor (respectively in the interstices of three-core cables) to oil expansion vessels in which the oil is stored under pressure. When the load is reduced and the cable is cooling down, the vessel forces the oil back into the cable. Therefore voids in oil-impregnated cables can never occur.

A metallic sheath covers the impregnated core, which can be an extruded lead sheath with reinforcement or a corrugated aluminum sheath. Over the metallic sheath an anti-corrosion protection layer (compound) is applied, followed by an extruded oversheath (PE or PVC).

Low pressure oil filled cables are used up to a rated voltage of 500 kV. Cables for higher rated voltages have already been developed and successfully tested. The power frequency withstand stress of this type of cables is about 40 kV/mm and the maximum stress under operating conditions varies between 10 and 15 kV/mm. The insulation thickness is normally designed on the basis of the maximum permissible lightning impulse stress in the range of 90 - 95 kV/mm depending on conductor design.

b) Low pressure oil filled cable with polypropylene paper laminate insulation

The use of low pressure oil filled cables with conventional paper insulation at extra high voltages (> 500 kV) is limited due to the dielectric losses, which are proportional to the square of U_0. Therefore an alternative tape material - polypropylene paper laminate (PPL) has been developed. The dielectric loss factor of low pressure oil filled cables with PPL insulation is about 2.5 - 3 times lower compared to conventional paper insulation.

The design of the complete cable is similar to that of conventional low pressure oil filled cables. Insulation thicknesses are also determined using the maximum permissible lightning impulse stress, which is in the range of 100 to 110 kV/mm due to the better material properties of PPL. The maximum power frequency withstand stress is about 45 kV/mm, the maximum stress under operating conditions is 17 to 20 kV/mm.

These types of cables a) and b) were called LPOF cables until the 1970’s, when synthetic dielectric liquids began to replace the mineral oils that had been used earlier. The usual name is now Self Contained Liquid Filled (SCLF) or Self Contained Fluid Filled **(SCFF) Cables**.

c) High pressure oil filled cables

This type of cable consists of three impregnated paper insulated conductors, which are drawn into a steel pipe. The steel pipe is subsequently filled with oil and maintained under a pressure of approximately 15 bar. Due to this high operating pressure the insulation remains free of voids during any condition of operation. Regulating equipment consisting of pressure monitors, pumps and valves, controls the operating pressure. When the load increases and the cable is heating up, the expanding oil flows into a storage container. During the cooling period the oil is pumped back into the cable.

High pressure oil filled cables have been constructed for rated voltages up to 500 kV. This type of cables has not been used in recent installations. The AC withstand stress is approximately 50 kV/mm and the lightning impulse withstand stress 100 kV/mm.

d) External gas pressure cables

The paper insulated cores of external gas pressure cables are impregnated with high viscosity synthetic oil. Directly over the core a gas tight diaphragm lead sheath is applied which is exposed to an external gas pressure of about 15 bar. During heating periods the lead sheath expands due to the internal pressure of the expanding impregnating oil. When the cable cools down, the external gas pressure forces the lead sheath back to its original position. In this way the insulation remains free of voids. To enable this action of the diaphragm lead sheath the conductors are oval-shaped. External gas pressure cables can either be designed as self contained cables (earlier installations) or as pipe type cables (more recent installations). Pipe type cables consist of three cores pulled into a common steel pipe. The steel pipe is filled with compressed nitrogen. External gas pressure cables are used up to rated voltages of 275 kV. The typical lightning impulse design stress is in the range of 85 to 95kV/mm; typical operating stresses vary from 8 to 13 kV/mm.

e) Internal gas pressure cables

The insulation of internal gas pressure cables is impregnated with a high viscosity non draining insulating compound. This cable, in contrast to external gas pressure cable does not have a sheath. Either individual non-laid-up cores, each protected by a gliding wire, or laid-up multi-core cables with flat steel wire armour are fed into a steel pipe. The pipe is filled with nitrogen at a pressure of about 15 bar. The gas can penetrate the insulation and fill any voids, which are formed in the insulation by expansion and contraction during thermal cycles. Due to the high pressure of the gas inside the voids, ionisation is suppressed.

The maximum rated voltage, for which internal gas pressure cables are used, is 110 kV. Typical values for the lightning impulse design stress vary from 80 to 90 kV/mm. Under operating conditions the maximum AC stress is usually 8 - 10 kV/mm.

	Low Pressure Oil-Filled Cables (LPOF) **Also Called SCFF**		High Pressure Oil-Filled Cables (HPOF)		High Pressure Gas-Filled Cables (HPGF)	
Voltage Class	Up to Um=170kV	Above Um=170kV	Up to Um=170kV	Above Um=170kV	Up to Um=170kV	Above Um=170kV
	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm
AC Voltage	10	15	10	14	8	10
Lightning Impulse (Design Criteria)	85	95	80	90	60	80
Switching Impulse	75	85	70	80	50	70

Table 1 Typical Stresses in Service for Lapped Cables

4.2 Insulation design of high voltage AC cables with extruded insulation

An extruded layer of polyethylene (PE), cross-linked polyethylene (XLPE) or ethylene-propylene rubber (EPR) around the conductor forms the insulation of such cables. The shape of the conductor is circular for high voltage cables.

The surface of the conductor is more or less irregular due to the interstices between the single wires. To avoid electrical stress concentrations at such irregularities an extruded layer of semi-conductive material is applied on the conductor surface. For high voltage cables it is essential to form a pure radial electric field inside the insulation. Therefore an extruded semi-conductive material is applied also over the insulation.

In order to achieve a satisfactory long duration AC withstand characteristic it is necessary to avoid ionisation (partial discharges, PD) which can take place in gas filled voids inside the insulation and at the interfaces between the insulation and the semi-conductive layers. This is achieved by using properly defined process parameters and by bonding the three extruded layers.

An extruded lead sheath, an aluminium sheath or a wire screen encloses the insulated core. For some applications the cable is provided with reinforcement. Over sheath/screen, there is an extruded oversheath (PE or PVC).

Cables with extruded insulation are now currently used up to a rated voltage of 500 kV. The power frequency withstand stress of this type of cables is about 40 kV/mm, the maximum stress under operating conditions usually varies up to 16 kV/mm. Insulation thickness are normally designed on the basis of the maximum permissible AC voltage stress.

	Polyethylene **(PE)**			Cross-linked Polyethylene **(XLPE)**		
Voltage Class	≤ 170 kV	170<Um≤300 kV	Um>300 kV	≤ 170 kV	170<Um≤300 kV	Um>300 kV
	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm
ACVoltage Design Stress	7	11-12	**16**	7	11-12	16
Lightning Impulse	70	80	**80**	70	80	80
Switching Impulse	60	70	**70**	60	70	70

Table 2: Typical Stresses in Service for Extruded Cables

5 Recent Advances in both Lapped and Extruded Cables

5.1 Experience with Lapped Cables

5.1.1: The Italian experience with UHVAC Lapped cables [1]

In the years 1981-1986 a full scale tests qualification program have been carried out and completed at CESI on a cable system for use at the maximum rated voltage Umax of 1100kV. The program was positively concluded and it was demonstrated that a three phase 1100 kV underground Self Contained Fluid Filled (SCFF) cable system with cellulose paper insulation can be capable of transmitting the continuous load of 3000 MVA during normal operation and the overload of 9000 MVA during emergencies.

Paper 2-5-4 presented in IEC/CIGRE UHV Symposium in Beijing (2007- July 23rd)[1] gives details of these tests, shows the test circuit, and proposes further improvements by using Propylene Paper Laminate insulation in place of cellulose paper insulation .The main advantage of PPL is derived from its lower dielectric loss factor, which significantly reduces the losses generated within the insulation, as compared to cellulose paper. The loss factor is the product of the dielectric loss angle and the relative permittivity. A comparison between paper and PPL is given below:

	PAPER	PPL
Dielectric Loss Angle at 90°C	**2.4 x 10^{-3}**	**1.0 x 10^{-3}**
Relative Permittivity	**3.4**	**2.7**
Dielectric Loss Factor at 90°C	**0.0084**	**0.0027**
Thermal Resistivity	**5.0**	**5.5**

Table 3: Comparison between Characteristics of Cellulose Paper and PPL Insulated Cables

Forced water lateral cooling polyethylene pipes were applied to compensate the joule and dielectric losses in normal operation. Additional forced circulation and cooling of the oil inside the central duct was provided in order to sustain the overheating, overloading, emergency condition A further advantage with PPL arising from the lower value of relative permittivity is that for the same cable size (in terms of dimensions and electrical design stress) the capacitance of the cable is reduced.
This reduces the charging current and the amount of reactive compensation required in networks where there is a large quantity of underground cable installed. Today, with increasing focus on the cost of investments and losses, this is becoming a significant factor.
Further benefits in terms of external factors include less need for forced external cooling, which may change the design approach to UHV systems compared to past experience.

Fig 4: 1100kV SCFF Cable

Oil Duct Diameter	**24mm**
Conci Conductor	**2000mm²**
Insulation thickness	**35mm**
Lead sheath bitumen covered	
Hard drawn coper tape reinforcement	
PVC Outersheath	
Overall Diameter	**152mm**
Weight	**58kg/m**
Operating stress at conductor	**30kV/mm**
Operating oil pressure	**1.4 Mpa**
Operating temperature	**90°C**

Table 4: Cable structure

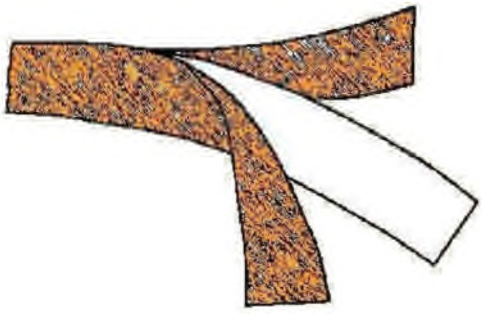


Fig 5: Typical PPL Laminate

5.1.2 Lapped Cables: 800 kV SCFF Cable tested at IREQ (CIGRE Report 21/22-04 at 1996 Session)

In 1996, report 21/22-04 titled "**Development and testing of a 800 kV PPLP insulated oil-filled cable and its accessories**"[2] describes in detail the test program of a 800-kV AC PPLP-insulated low-loss oil-filled cable developed to validate the PPLP technology for Hydro-Québec's future 765-kV St. Lawrence under-river crossings. It gives the design criteria and electrical characteristics of the cable and accessories, and reports the test lines construction, test program and main results obtained. The successfully completed test program has shown the very good performance of the PPLP-insulated cable and accessories for bulk power transmission, and led to special and original designs, studies, tests and computer programs.

The conclusion of the report was

The development and testing of the cable system described in this report was initiated to validate the most promising technology for 800-kV AC cables with a current-carrying capacity of 3000 A for future underwater crossings. The choice of PPLP insulation was governed by the necessity to have a low-loss compact cable with as small a conductor as possible. The required insulation level for the 800-kV AC cable system is 1800 kV and 1550 kV for lightning and switching impulse respectively. Type tests followed by a field aging test closely simulating operation of the cables under the concrete floor of an under-river tunnel were successfully completed in 1994, four years after the initiation of the study. The completed test program has led to special and original designs, studies, tests, and computer software. It has shown the very good performance of the PPLP-insulated cable and accessories designed to satisfy the service conditions and insulation levels required.

Item	Description
Fluid Channel Diam	25 mm
Conductor Section	2000 mm²
Conductor Shape	Milliken, 9 segments
Insulation Material	PPLP
Insulation Thickness	30mm
Insulating Fluid	DDB
Lead Sheath Thickness	4.7 mm
Oversheath Thickness	7 mm
Overall Diameter	154 mm
Weight	60 kg/m

Table 5 Cable Caracteristics

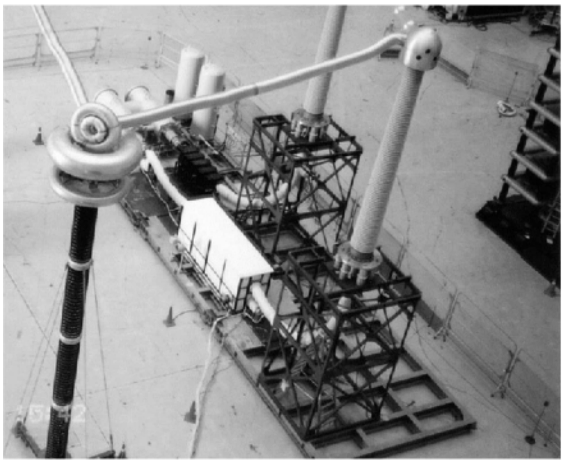


Fig 6 : Test Setup

These two examples given in 5.1.1 and 5.1.2 show that the technology of SCFF cables with PPL insulation is already suitable for UHV underground solutions, for example in case of river or fjord crossings as an underground section in an UHV Overhead Line .

The following examples will explain why extruded cable system solutions can also be envisaged at 800kV.

5.2 Experience of extruded cables systems at 500 kV

5.2.1 Extruded Cables: Paper 21-06 for CIGRE Session 2000 titled **“Construction of the world's first long-distance 500 kV XLPE cable line”** [15] introduces the longest 500 kV XLPE cable system installed in Tokyo and operated since 2000. The route length of the cable is 39.8 km. The cross section of the conductor is 2500 mm² Copper .Each phase comprises 40 joints (EMJ: Extruded Molded Joint) and two Gas-immersed GIS Terminations. The development, the design and the testing of the cable system have been presented in various papers.
Each Cable Circuit has a transmission capacity of 900 MW in the installation conditions (Tunnel)
The structure of the 500 kV XLPE Insulated cable and the characteristics are given in **Table 6.** A large delivery drum containing long section of cable is shown in **fig 7**.

Item		Unit	Spec
Nominal Voltage		kV	**500**
Numb of Conductors			**1**
	Area	mm²	**2500**
	Shape	**Sectoral / Compacted**	
	Outer D	mm	**61.2**
Inner Semicon		mm	**2.5**
Insulation Thickness		mm	**27.0**
Outer D on Insulation		mm	**120.2**
Outer Semicon		mm	**1.0**
Cushion Layer		mm	**3.5**
Aluminum Sheath		mm	**3.3**
Oversheath		mm	**6**
Outer Diameter		mm	**170**
Approximate Weight		Kg/m	**43.5**

Table 6: Characteristics of 500 kV 2500mm² XLPE Cable

Fig 7: Drum of 500 kV 2500mm² XLPE Cable

5.2.2 Extruded Cables: The report 21-104 presented in Paris Session 2002 [16] about XLPE Cable System describes and discusses the tests carried out on an XLPE cable system which, after passing the prequalification test at 400 kV, was successfully subjected to an additional prequalification test at 500 kV. On the basis of a statistical analysis of the breakdown tests of XLPE cables of similar construction and assuming a suitable reliability level in service , the conductor screen stress adopted to design the cable was 12 kV/mm for a rated voltage of 230/400 kV. The corresponding insulation screen stress of 6.2 kV/mm was not considered critical for the associated premoulded accessories.

In view of the good results obtained in the prequalification test at 400 kV, it was decided to continue the test and to check the safety margins of the system by attempting to prequalify the same assembly at 500 kV.
Before starting this test, the porcelain insulators of the two outdoor terminations under test were replaced with 500 kV porcelain insulators. **The EPR stress cones of these terminations were not touched during the porcelain replacement**.
The results of the 500 kV prequalification test were entirely successful and in full compliance with IEC 62067. As a consequence, XLPE cable systems with a conductor screen stress **of up to 15 kV/mm and an insulation screen stress of up to 7.8 kV/mm were qualified**. By the end of this test the cable system had been submitted to a voltage of 400 kV for 10176 hours and to a voltage of 500 kV for 9792 hours (more than one year at each voltage level)

Fig 8 Long-term Test

After the successful completion of the prequalification test at 500 kV, other tests for engineering information were carried out. The complete cable loop was submitted to 500 kV for 48 hours to confirm that the impulse test at BIL had not affected the system. Then an impulse test up to breakdown was performed on the section of the loop containing the joints. This assembly successfully withstood 1700 kV (+-10 shots) at 95 °C conductor temperature, and at this level the test was stopped, as the flashover level of the 400 kV laboratory outdoor termination had been reached.

In order to determine the impulse breakdown level, of the cable, 30 m of active length of cable was then cut in the section between the GIS termination and the outdoor termination and tested in the CESI EHV laboratory. The outer semiconducting layer of the cable was used as a resistive field control at the terminations and the voltage was raised in steps of 50 kV (+-10 shots) with a conductor temperature of 95°C. **The assembly withstood 2350 kV (±10 shots) and then the test was**

interrupted due to the limit of the test equipment. The conductor screen stress on the cable at this impulse voltage level was 123 kV/mm.

The conclusions of the report were:

- The CIGRE test recommendations published in Electra N°151 (and of course IEC 62067) [10][11][12][13][14] have been instrumental in facilitating the early deployment of EHV XLPE cable systems.
- The successful performance of a comprehensive series of tests based on the above recommendation has confirmed that 400 and 500 kV XLPE cable systems manufactured using properly selected materials and technologies and installed by skilled personnel using suitable techniques exhibit a high degree of reliability and considerable safety margins.
- The results of the above tests also indicate that the conductor screen design stresses of properly made EHV XLPE cables can be increased to values of the order of 15 kV/mm, thus matching the design stresses which have been adopted for many years in connection with EHV SCFF cables. In addition said test results indicate that, provided suitable premoulded accessories are used, insulation screen design stresses can be increased to values of the order of 8 kV/mm.
- Future test procedures should maintain a suitable balance between growing experience and the ongoing need for a thorough qualification process.

6 Discussion

From the various examples given in section 5, the following approach can be proposed towards UHV Cables within the frame of documents published by SC B1.

- **Lapped Cables** are available and fully tested at UHV levels (800 kV and 1000 kV). For the adoption of such cables, care has to be given to the dielectric losses. PPL technology is offering better solutions than cellulose paper options.
- **For XLPE cables**, design stresses for a safe operation during tens of years are of about **16 kV/mm** at the conductor and **8 kV/mm** over insulation. Further reduction of wall thickness is envisaged [17]. A small increase of 10% of these stresses seems achievable while keeping safety margins.
- Impulse Withstand Level is easily obtained for XLPE cables in the range of these service Electrical Fields since the ratio BIL/Service Voltage is decreasing with the increase of voltage.
- There is a size of extruded EHV cable that can be easily manufactured, transported and installed. Several installations worldwide with excellent service experience confirm this statement. Drums carrying more than 1000m of cables are available.
- Consequently, within the same diameter range, 800 kV extruded cables can be designed with Electrical Fields of 16 +10% kV/mm and 8+10% kV/mm as ***Emax*** and ***Emin.***
- As an example, with a diameter of cable core of 145 mm which means a diameter over insulation of 142 mm, and a conductor of 2500mm² having a diameter of 61.2 mm covered by a semicon layer of 2.5 mmm, we have d= 61.2+2.5+2.5 mm= 66.2mm and D=66.2+ 38+38=142 mm for an insulation thickness of 38 mm The resulting electrical stresses are **E_{max}=17.53 kV/mm** and **E_{min}= 8.10 kV/mm**, fully suitable. With the same expected ampacity as the 500 kV described in 5.2.1, the transmission capacity of such cable system would be approximately 900 MW* 800/500= 1440 MW per circuit in the same installation conditions.

7 HVDC Options

In May 2015, CIGRE organised Lund Symposium (27-28 May) fully dedicated to HVDC Transmission systems. On this occasion, on request of the Organising Committee, Study Committee

B1 presented a Tutorial titled" Prospects and Limitations in respect of future ratings of HVDC Cables. It was recalled that two technologies are available:

Mass Impregnated cables

- o Impregnated paper insulation
- o Maximum conductor temperature 55-85°C
- o Maximum voltage commercially available 600 kV

Extruded Cables

- o Polymer insulation
- o Maximum conductor temperature at least 70°C
- o Maximum voltage commercially available 500 kV
- o Robust

The prospects for higher voltages have also been presented

Mass Impregnated Cables: from 600 kV to 800 kV?

- 600 kV is now reached for PPLP (polypropylene laminated paper)

Extruded Cables: from 320 kV to 525 kV to higher voltages?

- Several players are working on higher voltage for extruded DC cable systems and recently the 525 kV level has been reached
- It is most probably not the limit

Several issues have to be taken into account:

- Accessories (i.e. the whole cable system)
- Impulse levels with superimposed DC voltage must match the higher voltage levels (CIGRE JWG B4/B1/C4 .73 is currently starting to address this issue)

The conclusion of the presentation was in fact a list of questions:

- Is there a need for standardization of DC system voltages?
- What further actions should CIGRE B1 take in the field of HVDC cable development?
- What experiences, that could limit the application of HVDC cable, have been collected so far?

Conclusion:

This paper is based on Cigre and IEC documentation. From the experience gained with EHVAC cable systems, it can be expected that 800 kV extruded cables will be soon available since the ageing process of the PE or XLPE insulation is well known. A small increase of only 10% of the electrical stresses currently used at 500 kV will allow the design of 800 kV cable systems with limited number of joints as lengths of 500 to 1000 Meters could be shipped.

Of course, extension of the current Standardization to cover 800 kV level will be necessary and be soon included in the work program of SC B1 to produce recommendations.

In the meantime, SCFF cable systems are already available. Their use has to be considered on a case by case basis, taking into account the dielectric losses. In this prospect, PPLP offers better performances.

Mass impregnated HVDC cable systems could be also available in the future at 800 kV.

UHVDC extruded cables will need more development testing to better understand the ageing process of the insulation, to better know actual the stresses in service and finally establish the recommendations for testing.

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