Tests on Extruded Cables

Pierre Argaut
Chairman of CIGRE SC B1

October 26th, 2011
At least, once in your life, you have heard these words:

- Development Tests
- Long-term Tests
- Prequalification Tests
- Extension of Qualification Tests
- Type Tests
- Factory Production (Routine) Tests
- Sample tests
- After-installation Tests
- Maintenance or Assessment Tests
- Special-purpose Tests

For a HV or EHV extruded cable system, all of them mean something
The 40 years Cable Life Cycle

Construction

Manufacturing

Design

Testing

Operation

Operation, Maintenance, Reliability

Cable & Accessories design

System design

Rating, Ampacity

Monitoring, Diagnostics

Removal

Fall ICC, 2011, Denver, Colorado
Contents

1 Introduction
2 What is Electrical Stress?
3 Design of the Insulation of a cable
   Development tests
4 How to prove the design of the cable system?
   Type Test
   Prequalification Test
5 How to control the quality of manufacturing?
   Routine Test
   Sample Test
6 How to check to correct installation of accessories?
7 Some specific purposes tests
8 Extension of Qualification Tests
The Cable Life Cycle

Manufacturing

- Material Selection
- Electrical Stress Adoption
- Type Testing
- PQ Testing
- Routine Testing
- Sample Testing

Design

- System design
- Rating, Ampacity
- Study of breakdown and ageing mechanisms

Construction, Installation

- Cable & Accessories design

Construction

Testing

Operation

- Operation, Maintenance, Reliability
- Monitoring, Diagnostics

Removal

After Installation
1 Introduction
LIFETIME CURVE

The diagram illustrates a lifetime curve with axes labeled as log E and log t. Key elements include:

- **Design Stress**: Represented on the operating stress line.
- **Operating Stress**: Represented on the design time line.
- **Safety Margin**: The vertical distance from the design stress line to the required lifetime line.
- **Design Time**: The horizontal distance from the design stress line to the required lifetime line.

The curve shows the relationship between stress and time, highlighting the safety margin required for the intended lifetime of a component or system.
Life Time Curve

• For a given insulation material, this lifetime curve can be established through development tests on:
  – Material samples (tapes/plates)
  – Model cables
  – Full size cables
Development tests
Electrical Field (or Stress)

- Electrical field on the conductor:
  - to establish the lifetime curve of the extruded insulation
  - to determine the B.I.L performance

- Electrical field over insulation:
  - to determine the interface between cable and accessory
Cables with lapped insulation

<table>
<thead>
<tr>
<th></th>
<th>Low Pressure Oil-Filled cables (LPOF)</th>
<th>High Pressure Oil-Filled cables (HPOF)</th>
<th>High Pressure Gas-Filled cables (HPGF)</th>
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<tr>
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<td>Up to $U_m = 170$ kV</td>
<td>Above $U_m = 170$ kV</td>
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<td>AC voltage</td>
<td>kV/mm</td>
<td>kV/mm</td>
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<td>Lightning Impulse</td>
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<td>95</td>
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<tr>
<td>(design criteria)</td>
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Cables with extruded insulation

<table>
<thead>
<tr>
<th></th>
<th>Polyethylene (PE)</th>
<th>Cross-linked Polyethylene (XLPE)</th>
<th>Ethylene Propylene Rubber (EPR)</th>
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<td>Lightning Impulse</td>
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### Large 400 kV projects

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<th>Cable</th>
<th>Cable length (km)</th>
<th>Conductor</th>
<th>Electrical stresses IN/OUT (kV/mm)</th>
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<td>84</td>
<td>1200 mm² Al stranded</td>
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2 What is Electrical Stress?
2. What is Electrical Stress?

- A screened core is effectively a cylindrical capacitor, with the conductor as the inner electrode and the core screen as the outer electrode.

For a conductor carrying a charge of $q$, an electrical flux emanates from the conductor radially giving a flux density at radius $x$ from the center of the conductor, defined by:

$$D_x = \frac{q}{2\pi x}$$

$$E_x = \frac{D_x}{\varepsilon_o \varepsilon_r} = \frac{q}{2\pi x \varepsilon_o \varepsilon_r}$$

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Work done in moving a unit charge from conductor surface to outer surface of insulation is determined as follows:

$$dW = -E_x dx \quad \Rightarrow \quad dV = -E_x dx$$

$$V = \int_R^r - E_x dx = -\frac{q}{2\pi \varepsilon_0 \varepsilon_r} \int_R^r \frac{dx}{x} = \frac{q}{2\pi \varepsilon_0 \varepsilon_r} \ln\left(\frac{R}{r}\right) \quad (V)$$

Rearranging:

$$\frac{q}{2\pi \varepsilon_0 \varepsilon_r} = \frac{V}{\ln\left(\frac{R}{r}\right)}$$

Since:

$$E_x = \frac{q}{2\pi x \varepsilon_0 \varepsilon_r}$$

Then:

$$E_x = \frac{V}{x \ln\left(\frac{R}{r}\right)} \quad (kV/mm)$$

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2. What is Electrical Stress?

$U_0 =$ phase voltage to earth

$D = 2R =$ diameter over XLPE insulation

$d = 2r =$ diameter over s/c conductor screen

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

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

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2. What is Electrical Stress?

- Example: 76/132(145) kV, 630mm² Copper XLPE cable

\[ U_0 = \frac{145}{\sqrt{3}} = 83.716 \text{ kV}, \quad D = 2R = 80 \text{ mm}, \quad d = 2r = 40 \text{ mm} \]

\[
E_{\text{max}} = \frac{2 \times (83.716)}{40 \times \ln\left(\frac{80}{40}\right)} = 6.0 \text{ kV/mm}
\]

\[
E_{\text{min}} = \frac{2 \times (83.716)}{80 \times \ln\left(\frac{80}{40}\right)} = 3.0 \text{ kV/mm}
\]
2. What is Electrical Stress?

- Relationship between Electrical Stress and distance from conductor (AC voltage 76/132(145) kV)
3 Design of Insulation thickness
3. Design of Insulation thickness

- Design of insulation thickness for HV and EHV cables is based on maximum stress or mean stress.
- Two field strengths are generally considered:
  1) the AC field strength
  2) the lightning impulse field strength
- The most complete approach is based on a statistical analysis of the reference strength.
- Statistical method takes into account the volume effect for the insulation breakdown and will be discussed later.
3. Design of Insulation thickness

- For design reliability, the following constraints should also be considered:
  - external stress allowed by the accessories ($E_{min}$)
  - acceptable AC breakdown risk level in service
  - AC voltage level for the routine test
3. Design of Insulation thickness

Previously we derived the equation for maximum stress ($E_{max}$). Rearranging, we can solve for insulation thickness:

$$D = d \cdot e^{\left(\frac{2U_o}{dE_{max}}\right)} \ldots .. mm$$

Thus Insulation thickness:

$$t = \frac{D - d}{2} \ldots .. mm$$
3. Design of Insulation thickness

- Curves of insulation thickness as a function of the conductor diameter and the maximum stress (AC voltage $U_m = 145kV$)
3. Design of Insulation thickness

- Curves of insulation thickness as a function of the conductor diameter and the **external electrical stress** \( E_{min} \) \( (U_m = 145kV) \)
3. Design of Insulation thickness

- If design criteria is based on external stress \( E_{\text{min}} \) or stress at the accessory interface, the following equation for insulation thickness can be easily solved with a few iterations:

\[
t = \frac{V}{E_{\text{min}} \ln \left( 1 + \frac{t}{r_i} \right)} - r_i
\]

\[
*3.3
\]

- \( t \) = insulation thickness (mm)
- \( r_i \) = internal radius of the insulation (mm)
- \( V \) = applied voltage (kV)
- \( E_{\text{min}} \) = external stress at accessory interface (minimum stress) (kV/mm)
3. Design of Insulation thickness

- When maximum stress and external stress are both considered, it is possible to plot insulation thickness as a function of the conductor diameter.

AC volt $U=145$ kV, $E(r_i)=7$ kV/mm, $E(r_e)=4$ kV/mm.
3. Design of Insulation thickness

- The maximum stress is predominant for small conductors.
- The external stress or minimum stress prevails for large conductors.
- For a voltage $U$ and a minimum stress $E_{\text{min}}$, insulation diameter can be expressed as a function of the inner radius of the insulation, thus, it is possible to determine an optimal cross-sectional area for which:

$$r_i = \frac{U}{E_{\text{min}}}$$

and

$$r_e = e^{1} \cdot r_i \approx 2.718 r_i$$
3. Design of Insulation thickness

Based on Mean Stress, $E_{\text{mean}}$, the well known Japanese method:

$$E_{\text{mean}} = \frac{V}{t} \text{ kV/mm}$$

**Insulation thickness needed to withstand AC voltage:**

$$t_{\text{AC}} = \frac{V_{\text{AC}}}{E_{\text{L(AC)}}}$$

$$V_{\text{AC}} = \frac{V}{\sqrt{3} \times k_1 \times k_2 \times k_3}$$

$V = \text{maximum line to line Voltage (kV)}$

$k_1 = \text{temperature coefficient}$

$k_2 = \text{deterioration coefficient}$

$k_3 = \text{allowance for uncertain factors}$

$E_{\text{L(AC)}} = \text{design strength (kV/mm)}$

**Insulation thickness needed to withstand lightning impulse voltage:**

$$t_{\text{imp}} = \frac{V_{\text{imp}}}{E_{\text{L(imp)}}}$$

$$V_{\text{imp}} = BIL \times k'_1 \times k'_2 \times k'_3$$

$BIL = \text{Basic Impulse Insulation Level (kV)}$

$k'_1 = \text{temperature coefficient}$

$k'_2 = \text{deterioration coefficient}$

$k'_3 = \text{allowance for uncertain factors}$

$E_{\text{L(imp)}} = \text{design strength (kV/mm)}$
3. Design of Insulation thickness

- Deterioration coefficient for AC voltages, $k_1$, can be obtained from the ratio between the time duration $t_w$ of withstand voltage test (h) and the expected life $t_o$ of the cable (h)

$$k_1 = n \sqrt[3.6]{\frac{t_o}{t_w}}$$

- It is determined by the inclination $n$ of the voltage-time curve.
3. Design of Insulation thickness

• For a reasonable value of $n = 12$ for XLPE cables, an expected cable life of 30 years and a one-hour withstand voltage test:

$$k_1 = \sqrt[12]{\frac{30 \times 365 \times 24}{1}} = 2.83$$

• Temperature coefficient, $k_2$, can be obtained from the ratio between breakdown strength at room temperature to the breakdown strength at 90°C

• $k_3$ gives allowance for unknown factors

• Values of $k_2 = 1.1$ and $k_3 = 1.1$ are commonly adopted
3. Design of Insulation thickness

- $E_{L(AC)}$ and $E_{L(imp)}$ can be obtained from cable insulation breakdown data which confirm to a Weibull distribution as shown:

$$F(E) = 1 - e^{-\left(\frac{E - E_L}{E_o}\right)^b}$$

*3.7

F(E) = Probability of breakdown occurring before stress E

$E_L$ = Location parameter

$E_o$ = Scale parameter

b = Shape parameter
3. Design of Insulation thickness

- Example of test data plotted on Weibull distribution paper:
4 How to prove the correct design?
Experience with HV extruded cables

The evolution of XLPE MV and HV systems commenced in the 1960s. In the 1970s, the first commercial 90-132-154 kV XLPE systems were installed in Europe and in Japan.

CIGRE WG 21.10 has published in Electra 137 a survey on the service performance on HV AC cable systems. The failure rate of extruded cable systems was very low (0.1 failures per 100 circuit km per year on cables and accessories - external failures were not included).

There are a number of designs of joints and terminations currently in use. At voltages up to and including 150 kV extruded insulation has largely superseded paper-insulated cables for new installations.

Much of the ‘good’ experience with HV XLPE cable systems is based on older cable construction with moderate design stresses.

Hence historical service experience with HV cable systems is not necessarily a good guide for the design of future systems. International Tests requirements were necessary.
How to prove the correct design?

- IEC test requirements have evolved over the years from the component based approach in IEC 840 to the system based approach, where accessories are considered together with the cable, in IEC 62067 and the most recent edition of IEC 60840.
- The IEC has published series of test specifications for HV and EHV cables, accessories and cable systems:
- In 1988, the first specification was published. IEC 840 (renamed later as IEC 60840) is for cables up to 150 kV (Um=170 kV). In this specification, type tests, routine and sample tests were prescribed for cables only.
How to prove the correct design?

• In 1999 IEC revised this specification and IEC 60840 Ed2 was published, in which accessories were included in type testing.

• In 2004 IEC published a third edition, IEC 60840 Ed3, in which type tests on cable system and routine and sample tests on prefabricated accessories were introduced.
How to prove the correct design?

- As cable makers started to develop EHV XLPE cable systems, they needed testing programmes both to monitor their own progress and to give customers confidence in the products being developed.

- Initially, these testing programmes were agreed on a local or national basis.
  - For example, France used a 250-cycles test for 6000 hours at U0, (this test was also performed on HV cables)
  - Belgium adopted a 100-cycles test at 2U0.
  - Japan used a half-year test at relatively low electrical stress based on the degradation factor of the insulation system.
Service experience with EHV extruded cable systems before publication of international Standard

- **Late 1970s**: First 220-275 kV XLPE systems installed
- **1980s**: Start-up of widespread commercial use of XLPE cables up to 230 kV
- **1989**: The first 275 kV XLPE systems with joints installed in Japan. Qualification using Japanese utility specifications
- **1969**: In France first installation of 225 kV low-density polyethylene (LDPE) cable, followed by more than 1000 km of LDPE cable with field-moulded joints and around 600 km of high-density polyethylene (HDPE) cables with good service experience.
- **1985**: in France first installation of 400 kV LDPE cables. In total, 40 km of cable and 21 back-to-back joints have been installed.
- **1999**: in France first installation of 400 kV XLPE cable
- **1988**: Commissioning in Japan of the world’s first 500 kV XLPE system followed by two subsequent circuits in 1988 and 1991 (short circuits without joints).
How to prove the correct design?

- Plans to install major 400 kV cable systems (Berlin, Copenhagen) led CIGRE to set up a Working Group to consider an international test specification. The tests were developed to give confidence that cable system passing the tests would have a fault rate in service lower than 0.2 faults/100km/year.

- In 1993 CIGRE WG 21-03 published a test program for cable systems above 150 (170) kV and IEC published a specification based on these documents IEC 62067 in late 2001.
Preamble of the 2001 Standard

• Such cables form part of the backbone of the transmission system and therefore, reliability considerations are of the highest priority;

• These cables and their accessories operate with higher electrical stresses than cables up to 150 kV and, as a result, have a smaller safety margin with respect to the intrinsic performance boundaries of the cable system;

• Such cables and accessories have a thicker insulation wall than those up to 150 kV and, as a result, are subjected to greater thermomechanical effects;

• The design and coordination of the cables and accessories becomes more difficult with increasing system voltages.
Background of CIGRE input

• While the type, special and routine test which are specified have been adequate at voltages up to 150 kV, and indeed operating experiences have proven this, they are not adequate on their own to cover the extension to higher voltage cables.

• It is considered that in order to gain some indication of the long term reliability of the proposed cable system, it is necessary to carry out a long term accelerated ageing test.

• The test should be performed on the complete cable system comprising cable, joints and terminations.

• The concept of performing such a test is well established in many countries

The test shall be called a prequalification test. This test is to be performed only once
3.2.4
prequalification test
Test made before supplying on a general commercial basis a type of cable system covered by this standard, in order to demonstrate satisfactory long term performance of the complete cable system. The prequalification test need only be carried out once unless there is a substantial change in the cable system with respect to material, manufacturing process, design and design levels.

NOTE A substantial change is defined as that which might adversely affect the performance of the cable system. The supplier should provide a detailed case, including test evidence, if modifications are introduced, which are claimed not to constitute a substantial change.

As it could have been difficult to understand what is a substantial change, on request from IEC, CIGRE WG B1.06 has issued recommendations on how to handle changes. These recommendations are published in CIGRE Technical Brochure TB 303.

Electrical Stresses are the basis of these recommendations.
Prequalification Test

• The prequalification test shall comprise the electrical tests on the complete cable system with approximately 100 m of full sized cable including accessories. The normal sequence of tests shall be:
  
  a) heating cycle voltage test;
  b) lightning impulse voltage test on cable samples
  c) examination of the cable system after completion of the tests above.

• NOTE - The prequalification test may be omitted if an alternative long term test has been carried out and satisfactory service experience can be demonstrated.
The pre-qualification test shall comprise the electrical tests on the complete cable system with approximately 100m of full sized cable including accessories. One year at 1.7 Uo with 180 heat cycles.
Range of approval PQ

- This Long Term Testing has been introduced as a "prequalification test PQ", which is described in paragraph 13 of IEC 62067.
- As indicated in paragraph 13.1, this test "qualifies the manufacturer as a supplier of cable systems with the same or lower voltage ratings as long as the calculated electrical stresses at the insulation screen are equal to or lower than for the cable system tested."
- Note: It is recommended to carry out a prequalification test using cable of a large conductor cross section in order to cover thermo mechanical aspects.”
Type Tests

Tests made before supplying on a general commercial basis a type of cable system, in order to demonstrate satisfactory performance characteristics to meet the intended application. Once successfully completed, these tests need not be repeated, unless changes are made in the cable or accessory materials, or design or manufacturing process which might change the performance characteristics.
Type Tests

Bending test on the cable
Partial discharge test at ambient temperature
Tang \( \delta \) measurement
Heating cycle voltage test
Switching impulse voltage test
Lightning impulse voltage test
Partial discharge tests
  - at ambient temperature and
  - at high temperature
Test of outer protection for buried joint
Range of approval TT

In § 12.2 of IEC 62067 - 2001 Range of type approval, it is stated that:

"When the type tests have been successfully performed on one cable system of specific cross section, rated voltage and construction, the type approval shall be accepted as valid for cable systems within the scope of this standard with other cross-sections, rated voltages and constructions if the following conditions are all met:

- **The voltage group is not higher than that of the tested cable system;**
- **The conductor cross-section is not larger than that of the tested cable;**
- **The cable and the accessories have the same or a similar construction as that of the tested cable system;**
- **Calculated maximum electrical stresses on the conductor and insulation screens, in the main insulation part of the accessory and in boundaries are equal to or lower than for the tested cable and accessory.**
Electrical Stresses (or fields)

- **Electrical field on the conductor:**
  - to establish the lifetime curve of the extruded insulation
  - to determine the B.I.L performance

- **Electrical field over insulation:**
  - to determine the interface between cable and accessory
### Large 400 kV projects

Following recommendations of CIGRE or IEC 62067

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<td>PE with flame retardant varnish</td>
<td>48 composite pre-fabricated</td>
<td>6 outdoor porcelain</td>
<td>Tunnel + forced ventilation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>39</td>
<td>2500 mm²</td>
<td>Al Welded laminated sheath</td>
<td>PE flame retardant</td>
<td>48 premoulded one piece</td>
<td>6 outdoor porcelain</td>
<td>Tunnel + forced ventilation</td>
<td></td>
</tr>
<tr>
<td>London</td>
<td></td>
<td>60</td>
<td>2500 mm²</td>
<td>Cu wires</td>
<td>PE with flame retardant varnish</td>
<td>60 composite pre-fabricated</td>
<td>6 GIS</td>
<td>Tunnel + forced ventilation</td>
<td></td>
</tr>
<tr>
<td>Jutland</td>
<td></td>
<td>84</td>
<td>1200 mm²</td>
<td>Al stranded</td>
<td>PE with semi conducting layer</td>
<td>96 premoulded one piece</td>
<td>36 outdoor composite</td>
<td>Direct buried and ducts</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1200 mm²</td>
<td>Al wires</td>
<td>PE with semi conducting layer</td>
<td>96 premoulded one piece</td>
<td>36 outdoor composite</td>
<td>Direct buried and ducts</td>
<td></td>
</tr>
</tbody>
</table>
5 How to control the quality of the manufacturing?
How to control the quality of the manufacturing?

Through routine tests and sample tests

**Routine tests**
- Tests made by the manufacturer on all manufactured components (length of cable or accessory) to check that the component meets the specified requirements.

**Sample tests**
- Tests made by the manufacturer on samples of complete cable or components taken from a complete cable or accessory, at a specified frequency, so as to verify that the finished product meets the specified requirements.
Routine Test

The following tests shall be carried out on each manufactured length of cable and on the main insulation of each prefabricated accessory, to check that the whole of each length and that the main insulation of each prefabricated accessory complies with the requirements.

a) partial discharge test ;

b) voltage test ;

c) electrical test on oversheath of the cable, if required .
Partial Discharge/Voltage Test

- The voltage test shall be made at ambient temperature using an alternating test voltage at power frequency.
- The test voltage shall be raised gradually to the specified value which shall then be held for the specified time between the conductor and metallic screen/sheath according to specified value.
- No breakdown of the insulation shall occur.
Sample Tests

The following tests shall be carried out on samples which, for the tests in items b) and g), may be complete drum lengths of cable, taken to represent batches.

a) conductor examination;
b) measurement of electrical resistance of conductor;
c) measurement of thickness of insulation and oversheath;
d) measurement of thickness of metallic sheath (see 10.7);
e) measurement of diameters, if required;
f) hot set test for XLPE and EPR insulations;
g) measurement of capacitance;
h) measurement of density of HDPE insulation;
i) lightning impulse voltage test followed by a power frequency voltage test;
j) water penetration test, if required.
Sample Tests: frequency

• The sample tests in items a) to h) shall be carried out on one length from each batch of the same type and cross-section of cable, but shall be limited to not more than 10% of the number of lengths in any contract, rounded to the nearest whole number.

• The frequency of the tests in items i) and j) shall be at the discretion of the manufacturer but shall at least comply with the following:

  Size of the order
  – above 4 km and up to and including 20 km: 1 sample
  – above 20 km: 2 samples
Routine and Sample Tests

Faraday cage and Transformer for Routine Testing

Fall ICC, 2011, Denver, Colorado
Equipment for Sample Testing

Sample testing cable+accessories of a 400 kV cable system

Fall ICC, 2011, Denver, Colorado
6 How to check the quality of the installation of accessories?
Commissioning tests

• Proving the wiring that provides remote control, signalling and measurement equipment.
• Tests for correct operation of remote control, signalling and measurement equipment.
• Checking the electrical clearances and conductor sag for the jumpers
• When use of DTS, taking the initial Route Temperature Profile of the system
• Tests after installation of underground sections
  • test of the oversheath
  • electrical test of the main insulation
Electrical Tests After Installation

Tests on new installations are carried out when the installation of the cable and its accessories has been completed.

An oversheath test and/or an a.c. insulation test is recommended. For installations where the oversheath test is carried out, quality assurance procedures during installation of accessories may, by agreement between the purchaser and contractor, replace the insulation test.
Electrical Tests after Installation

DC voltage test of the oversheath
The voltage level and duration specified in clause 5 of IEC 60229 shall be applied between each metal sheath or concentric wires or tapes and the ground. For the test to be effective, it is necessary that the ground makes good contact with all of the outer surface of the oversheath. A conductive layer on the oversheath can assist in this respect.

AC voltage test of the insulation
The a.c. test voltage (20 Hz to 300 Hz) to be applied shall be subject to agreement between the purchaser and the contractor. The waveform shall be substantially sinusoidal. The voltage shall be applied for 1 h, either with a voltage according to table 10 or with 1,7 $U_0$, depending on practical operational conditions. Alternatively, a voltage of $U_0$ may be applied for 24 h.
Tests of the underground section

(ref: Electra 173, 1997 by WG 21-09/2 and IEC 62067

– 24 Hours at Uo

– Higher test voltages from 1.1 to 1.7 Uo with dedicated equipment
  • access in the vicinity of termination
  • distances between live parts and surrounding equipment
Electrical tests on HV/EHV cable circuits
Electrical Tests

- Power Supply (260 kV, 83 Amp) (parallel connection)
- Blocking Impedance
- Corona Rings
- Capacitive Voltage Divider
- Test Bus (also electrical screen)
7 Some Special Purpose Tests
Some Special Purpose Tests

Corrosion test on laminate coverings

Short Circuit Test
8 Extension of qualification Tests
Extension of qualification

• This item will be addressed in a further Educational Session
Thank You for your attention

Questions?