High Voltage AC Power Cable Insulation Design

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Outlines

- Introduction
- Insulated cables and components
- High voltage AC cable insulation
- Electric field distribution in cable
- Factors governing the performance
- Insulation design (insulation thickness determination)
- What’s next
- An example
- Manufacturing processes
Introduction

- Electric energy forms a key part of our everyday lives.
- It needs to be transferred from generating sites (power plants) to substations located near to population and industrial centres.
- Electricity is transmitted at high voltages (110 kV or above) to reduce the energy lost in long distance transmission.
- Transmission via either overhead lines or insulated cables
<table>
<thead>
<tr>
<th>Overhead lines</th>
<th>Cables</th>
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<tbody>
<tr>
<td>Cheap (air is a good insulation)</td>
<td>Expensive (insulating materials)</td>
</tr>
<tr>
<td>Easy to maintain</td>
<td>High repair cost</td>
</tr>
<tr>
<td>Audible noise emission</td>
<td>Less space required</td>
</tr>
<tr>
<td>Radio and TV interference</td>
<td>Well screened</td>
</tr>
<tr>
<td>Emission of ozone and oxides of nitrogen</td>
<td>Environmental clean</td>
</tr>
<tr>
<td>Safety and comfort problems caused by electrostatic fields</td>
<td>No direct safety threat</td>
</tr>
<tr>
<td>Suitable for rural area</td>
<td>Suitable for urban</td>
</tr>
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</table>
Typical cables and components

- Conductor (Copper and aluminium)
- Semiconducting screens (Carbon paper and carbon loaded polymer)
- Insulation (Paper, PVC, XLPE, PPLP and EPR)
- Screen of copper wires
- Metallic sheath (Lead, lead alloy and corrugated aluminium alloy)
- Other protection (PVC and HDPE)
Insulating materials for high voltage AC cables

- Paper/oil insulation system
- Crosslinked polyethylene (XLPE)
- Paper/polypropylene laminated insulation system (PPLP)
- SF₆ gas

Features of two main insulation for HVAC

<table>
<thead>
<tr>
<th>Paper/oil</th>
<th>XLPE</th>
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<tbody>
<tr>
<td>Long history of reliability</td>
<td>Low permittivity</td>
</tr>
<tr>
<td></td>
<td>Low tanδ</td>
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<tr>
<td>More tolerant to dc test</td>
<td>High breakdown strength</td>
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<td></td>
<td>Easy to process/extrude</td>
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Advantages of XLPE insulation over paper/oil

- Reduced weight
- Accessories are easily to be applied
- Easier to repair faults
- No hydraulic pressure/pumping requirements
- Reduced risk of flammability/propagation
- Economics
  - Reduce both initial and lifetime costs
Evolution of the Highest AC Cable Voltage

The electric field under AC is determined by permittivity of the insulation (capacitive grading).

\[ E(r) = \frac{V}{r \ln\left( \frac{R}{r_0} \right)} \]

The electric field shows its maximum value at the surface of the conductor!

The minimum value of \( E(r_0) \) is found when \( R=2.718r_0 \) i.e. \( E(r_0)_{\text{min}}=V/r_0 \).

This optimum relationship is always overridden by other considerations for conductor radius.
Permittivity of an insulation material changes little with temperature and electric field, i.e. electric field distribution under AC conditions remains almost the same over its operational life.

The electric field under DC is determined by conductivity of the insulation (resistive grading) which is a function of both temperature and electric field.

The electric field under DC is therefore changes with loading conditions. Under a full load, the maximum electric field occurs at the insulation screen and may be higher than that under AC conditions.

Another important factor affecting electric field is the easy formation of space charge under dc conditions which will cause further field distortion.
Factors governing the performance

- Voids
- Protrusions
- Impurities
- Moisture

Voids – Partial discharges

The presence of voids under high electric field leads to partial discharges (PD).

PD may cause material degradation, resulting in a shorter life time of insulation.
Protrusions - Electrical treeing

An electrical pre-breakdown phenomenon due to damages caused by partial discharges and it can progresses through the stressed dielectric insulation in different forms.

Branch tree
Mixed tree
Bush tree
Defects and moisture - Water treeing

Degradation of insulation materials under the influence of both moisture and electric field.

Water trees growing from the inner (left), outer (middle) semi-conductive screens and final failure (right).
Improvement in the minimum breakdown strength used in XLPE cable insulation design
Insulation design

AC design

\[ t_{ac} = \frac{(V_0 / \sqrt{3}) \times k_1 \times k_2 \times k_3}{E_{ac}} \]

where
- \( t_{ac} \) – insulation thickness needed for AC
- \( V_0 \) – nominal maximum line voltage
- \( k_1 \) – temperature coefficient
- \( k_2 \) – degradation coefficient
- \( k_3 \) – allowance for other indeterminate factors
- \( E_{ac} \) – minimum breakdown strength for AC
Impulse design

\[ t_{imp} = \frac{BIL \times k_1' \times k_2' \times k_3'}{E_{imp}} \]

where  \( t_{imp} \) – insulation thickness needed for impulse voltage

\( BIL \) – basic impulse insulation level

\( k_1' \) – temperature coefficient

\( k_2' \) – degradation coefficient

\( k_3' \) – allowance for other indeterminate factors

\( E_{imp} \) – minimum breakdown strength for impulse voltage
Parameter determination

Electrical breakdown strength of insulation material

Electrical breakdown event is controlled by defects in insulation material and is statistic in nature.

Weibull distribution is generally accepted to analyse breakdown data. The survival probability $P(t, E)$ is given by

$$P(t, E) = \exp \left[ -\left( \frac{t}{t_0} \right)^a \left( \frac{E}{E_0} \right)^b \right]$$

where $a$, $b$, $t_0$, and $E_0$ are the Weibull parameters for a particular insulation (with particular dimensions).

Electrical breakdown is affected by several factors such as duration of the applied voltage and temperature.

Weibull plots for XLPE cables

To obtain a reliable breakdown strength for a material many samples are required.

AC breakdown strength of XLPE is lower than impulse breakdown strength!
The bathtub curve

The lifetime of a population of products can be represented by a graph called the bathtub curve.

The curve consists of three periods:
(i) an infant mortality period with a decreasing failure rate,
(ii) a normal life period (also known as "useful life") with a low, relatively constant failure rate,
(iii) a wear-out period that exhibits an increasing failure rate.

Similar curve occurs for cable insulation as evidenced from the Weibull plots for both AC and impulse breakdown. From a customer satisfaction viewpoint, infant mortalities are unacceptable and undermine customer confidence.
They are caused by defects designed into or built into a cable. Therefore, to avoid infant mortalities, the cable manufacturer must determine methods to eliminate the defects.
$E_{\text{max}}$ or $E_{\text{mean}}$?

Many cable samples with different dimensions are usually required to identify which electric field should be used to design insulation thickness.

If the breakdown stress is dependent on the volume of the insulation, it indicates the breakdown is taken to be governed by $E_{\text{mean}}$.

If the breakdown stress is dependent on the area of the electrode (internal conductor area), it indicates the breakdown is governed by $E_{\text{max}}$.

Currently, $E_{\text{mean}}$ is widely used for XLPE cable design, i.e.

$$E_{\text{mean}} = \frac{V}{R - r_0}$$
If a predefined survival probability is agreed it is possible to derive from the Weibull distribution the life of a cable and its relationship with the applied electric field at constant temperature. It has been found the life time of the cable is governed by the inverse power law.

\[ tE^N = k \text{(const.)} \]

where
- \( t \) = the lifetime
- \( E \) = the applied electric field
- \( N = b/a \), power index.

This law is utilised by maintaining a constant stress on the cable and measuring time to failure.

Life under service conditions is obtained by extrapolating the straight line resulting from the plot of \( \text{Log}(E) \) versus \( \text{log}(t) \).

This assumes that the same mechanism which has operated at high stresses operates at the service stress.
Health expert says that stress can kill people.

Insulation expert says that higher electric stress (field) can deteriorate insulation material and reduce its life span.

Accelerating ageing tests are necessary to establish N and the constant in the inverse power law.

Providing the same mechanisms involved in ageing processes, the inverse power law allow us to predict service life of XLPE cables.

N value is required to establish $k_2$ (degradation coefficient) in AC thickness, $t_{ac}$, calculation.

Data collected from the literature for high voltage AC XLPE cables with different conductor sizes and insulation thicknesses.
The relationship between life time and temperature and their effect on insulation has been studied for many years.

- In 1930, the concept of the \(10^\circ\text{C}\) rule was introduced, i.e. the thermal life of insulation is halved for each increase of \(10^\circ\text{C}\) in the exposure temperature.

- In 1948, Dakin postulated that the rate of thermal ageing of insulation was another way of stating that the rate of temperature induced changes (deterioration) obeyed the Arrhenius chemical rate equation.

\[
k = A \exp\left(-\frac{E_a}{RT}\right)
\]

where

- \(k\) = rate constant
- \(T\) = absolute temperature (K)
- \(A\) = constant for a material
- \(E_a\) = thermal activation energy
- \(R = 8.314 \text{ J/mol K}\), a gas constant.

Using this basic concept, the life (time-to-failure) of insulation aged at elevated temperatures can be expressed as

\[ L = B \exp\left(\frac{E_a}{kT}\right) \]

where \( L = \text{the life in units of time} \)
\( B = \text{a constant, usually determined experimentally} \)
\( k = \text{the Boltzmann constant}. \)

If we take the natural logarithm and rearrange the terms, it becomes a generalized expression for a straight line

\[ \ln(L) = \ln(B) + \frac{E_a}{kT} \]

This is the equation widely used in insulation design in terms of temperature effect on the lifetime of insulation.
If the logarithm of the life of the insulation is plotted vs. the reciprocal of the absolute temperature, a straight line is obtained.

Electric strength against ageing time.

Thermal endurance of XLPE cables based on electric breakdown strength (endpoint 50% - IEC 216) aged at 110, 130 and 150°C.

What is next?

A typical cable transmission system consists of cable, joints and terminations (cable accessories).

There must be an insulation coordination with the performance of cable accessories. Various tests have to be carried out prior to the practical operation of a cable system.

<table>
<thead>
<tr>
<th>Test</th>
<th>Objectives</th>
<th>Time</th>
<th>Piece</th>
</tr>
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<tbody>
<tr>
<td>Development</td>
<td>Simulation of operating stress Estimate long term behaviour Determination of dimension parameters</td>
<td>In-phase of new and future development</td>
<td>Full-sized cables &amp; accessories Model cables</td>
</tr>
<tr>
<td>Pre-qualification</td>
<td>Proof of operational suitability Estimation of long term behaviour Confirmation of customer requirements</td>
<td>At the start of important projects If required by customer</td>
<td>Full-sized cables &amp; accessories</td>
</tr>
<tr>
<td>Type</td>
<td>Proof of operational suitability Proof of properties specified in standards Confirmation of customer requirements</td>
<td>After conclusion of development On change of design and material If required by customer</td>
<td>Full-sized cables &amp; accessories</td>
</tr>
<tr>
<td>Sample</td>
<td>Proof of properties specified in standards</td>
<td>After manufacture of special part of order</td>
<td>Individual components</td>
</tr>
<tr>
<td>Routine</td>
<td>Proof of properties specified in standards Manufacturing check, quality assurance</td>
<td>Before delivery to site</td>
<td>Every length &amp; accessory supplied</td>
</tr>
<tr>
<td>On-site</td>
<td>Installation check, quality assurance Proof of readiness to switch on Estimation of ageing condition</td>
<td>After laying After repair After long service time</td>
<td>Complete cable systems</td>
</tr>
</tbody>
</table>
An example – Japanese experience


To determine parameters in $t_{ac}$ and $t_{imp}$, various experimental work was done.

Pre-breakdown partial discharge method was used to identify factors governing the performance -- impurities

Various sizes of model XLPE cables were used to examine size effect. Weibull distribution was used to analysed the data. Both $E_{max}$ and $E_{mean}$ were plotted against the size.

$E_{mean}$ was a preferred choice as electric field notation.
Short term electrical performance

Effect of insulation thickness

Assume that the maximum insulation thickness for 500 kV XLPE cable is 30 mm, then $E_{ac} = 40 \text{ kV/mm}$. Similarly, $E_{imp} = 80 \text{ kV/mm}$ is obtained for 30 mm thick insulation.
AC long term characteristics

The applied electric field and life time characteristics for cable A.

Breakdown has not occurred at 3000 hrs, from which it is inferred that the degradation exponent $N > 20$.

Considering the allowance, in the design of 500-kV XLPE cable $N = 15$ as the degradation exponent.

By taking the ratio of the design lifetime of 30 years to the 1-hour evaluation time of $E_{ac}$, this yields as the degradation coefficient the value

$$k_2 = \sqrt[15]{\frac{30 \times 365 \times 24}{1}} = 2.3$$

Repeated impulse tests showed no significant effect on degradation. Considering the limited number of surges over the life time, $k_2'$ was set to unity, i.e. $k_2'=1$.

Temperature characteristics

Breakdown strength and temperature characteristics.

Based on the breakdown strength and temperature characteristics for both AC and impulse voltages of XLPE cable, the following temperature coefficients were chosen:

$k_1 = 1.2$ for AC voltage and

$k_1' = 1.25$ for impulse voltage.
**Design of insulation thickness**

Based on the experimental results, design parameters for 500 kV XLPE cable are summarised (coefficient for uncertain factors is set to 1.1).

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>Impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum line voltage</td>
<td>$V_m$ = 550 kV</td>
<td>-----</td>
</tr>
<tr>
<td>Lightning surge overvoltage</td>
<td>-----</td>
<td>$BIL = 1425$ kV</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>$k_i$ = 1.2</td>
<td>$k_i'$ = 1.25</td>
</tr>
<tr>
<td>Degradation coefficient</td>
<td>$k_2$ = 2.3</td>
<td>-----</td>
</tr>
<tr>
<td>Repeated lightning impulse degradation coefficient</td>
<td>-----</td>
<td>$k_2'$ = 1.0</td>
</tr>
<tr>
<td>Allowance for uncertain factors</td>
<td>$k_3$ = 1.1</td>
<td>$k_3'$ = 1.1</td>
</tr>
<tr>
<td>Design stress (kV/mm)</td>
<td>$E_{ac}$ = 40</td>
<td>$E_{imp}$ = 80</td>
</tr>
</tbody>
</table>

Using the two formula for insulation thickness, the following thickness was obtained for AC and impulse voltage respectively.

$$t_{ac} = 24.3 \text{mm} \quad \text{and} \quad t_{imp} = 24.5 \text{mm}$$

By taking the larger of the insulation thicknesses determined for AC and impulse and rounding up, the required insulation thickness for 500-kV XLPE cable was set to $t = 25 \text{ mm}$. 
Main steps in power cable manufacture

Wire drawing

Paper insulated

- Paper lapping
- Drying & impregnation
- Metal sheathing
  - Pb
  - Reinforcement
- Final sheath

Polymer insulated

- Extrusion of insulation
  - Methane removal
  - Metal sheathing
- Final sheath
Extrusion Processes

- **Vertical Extrusion Line (VCV)**
  - High building or deep hole
- **Horizontal Extrusion Line (MDCV)**
  - Long land die, lubricant, speed, large conductors
- **Catenary Extrusion Line (CCV)**
  - Catenary shape, small conductors

**Extrusion Keywords:**
- Compound feed, True triple extrusion, X-ray dimensional scanning, Dry curing, Dry cooling, Stress relaxation, Post extrusion scanning.
Cable Manufacturing Processes

Vertical Continuous Vulcanization (VCV)

Continuous Catenary Vulcanization (CCV)
A typical VCV Line