Design of High Voltage Equipment

The design and construction of HV equipment requires experience in the application of the laws of electric fields. HV requirements often hinder a construction which is the best from the mechanical and thermal points of view.

Basic arrangement of the insulation system

Single material configurations
Multi-material configurations
Insulating configurations
Single material configurations

- **Examples:** air clearances in outdoor stations and the insulation of plastic cable
- **Field profiles of symmetrical and asymmetrical electrode configurations**

\[ V = \int_{0}^{s} E(x) \, dx \]
An important application: Increasing the breakdown voltage of vertical gaps or support insulators for a given spacing \( s \) by elevated mounting of the earthed electrode.
Multi-material configurations

- Occurs in most practical insulation systems
- Boundary surfaces present and boundary conditions apply:
  \[ E_{t1} = E_{t2} \quad \text{and} \quad \varepsilon_1 E_{n1} = \varepsilon_2 E_{n2} \]
- Impurities and humidity are unavoidable at the boundaries, leading to contamination layers
- An important construction requirement: keep the field strength at the boundary surfaces low – especially the tangential components.
A particularly favourable case is obtained if the boundary surface coincides with an equipotential surface ($E_t=0$) – Transverse boundary surface.

**Example:** Insulating barrier in a transformer -- During manufacturing, the barriers are moulded so that they follow the shape of the equipotential surfaces as far as possible.
Model configurations with longitudinal boundary surfaces

- a) Homogeneous edge field
- b) Inhomogeneous edge field

Model configurations with inclined boundary surfaces

- a) Embedded electrodes
- b) Electrodes arranged on the surface
Insulating configurations

Four types of insulators
- support insulator for transmission of compressive or flexural forces
- suspension insulators for transmission of tensile forces
- bushings for rigid penetration of the electrodes
- leads out for rigid leading out of a voltage-carrying electrode from an earthed region
Four Types of Insulating Configurations

a) support insulator
b) suspension insulator
c) bushing
d) lead-out (e.g. cable termination)
• For outdoor applications, the insulators are provided with sheds to increase the creepage path and to prevent the formation of unbroken water channels during rainfall.

• The shape of the shed depends on
  - material used for manufacture
  - anticipated pollution

• General guide for length of the creepage path
  2 to 4 cm per kV
Outdoor Insulators

Shed profiles of outdoor insulators
Porcelain:
a) cap-and-pin type insulator
b) long-rod insulator
c) equipment insulator
   (porcelain housing)

Plastic:
d) long-rod insulator
Coaxial support insulators for metal encapsulated gas insulated systems

a) disc-type, b) conical type, c) funnel type and d) funnel type for 3 pole encapsulation
Measures to Avoid Intensification of Electric Stress

• Uniform stressing results if each part of the insulation system under voltage is stressed by about the same proportion of the permissible value.

• In the design of an insulation system the stress distribution can be influenced by the arrangement of the electrodes and the insulating body.

• Attempt to avoid stressing the boundary surfaces or at least limit their stress to permissible values.
External Screening Electrodes

If the dimensions of the electrodes are small, the field strength is high around. External screening can improve homogenization of the stress.

Top-electrode made up of electrode elements
Internal Screening Electrodes

The field concentration at critical boundary surfaces can also be relieved by means of protruding internal electrodes.
Intermediate Electrodes

Homogenization of electric stress can be achieved by the insertion of intermediate electrodes.

Potential control for dc is obtained through the effective partial resistance.

Potential control for ac is obtained through the effective partial capacitance (more common).

Subdivision of the arrangement aims to yield approximately equal partial voltage.
Curve 1 – Ideal distribution
Curve 2 - Erath capacitance $C_{ev}$
Curve 3 – HV capacitance $C_{hv}$
Curve 4 – Resultant from Curves 2 and 3
For n-element doubly capacitor chain, given $C_{ev}$ and constant $C_v$, $C_{hv}$ can be calculated to obtain a linear voltage distribution.

The voltage drop across main $C_v$ should be equal to $\Delta U$ and add up to the external applied voltage $U=n\Delta U$. It follows from this that $i_v=i_{v+1}$ must be satisfied. The current for the junction then gives

\[
(U - U_v) \omega C_{hv} = U_v \omega C_{ev}
\]

with $U_v=v \Delta U$ one finally obtains

\[
C_{hv} = C_{ev} \frac{v}{n - v}
\]
High Voltage Bushings

- Bushing – the insulated penetration of one electrode by another.
- The interaction between insulating material and construction becomes particularly clear in the case of bushing, i.e. the same problem leads to completely different solutions for different materials.
- Bushings for ac voltages up to about 30 kV are made of porcelain or cast resin; for higher voltages, insulating bodies made of hardboard or soft paper in the wound construction and with porcelain housing are preferred.
A **bushing** is an component that insulates a high voltage conductor passing through a metal enclosure. Bushings appear on switchgear, transformers, circuit breakers and other high voltage equipment.
Field control in porcelain and epoxy resin bushings

Field control in a porcelain bushing:
1 shaft, 2 inner conductive coating, 3 insulating body, 4 outer conductive coating, 5 flange

Field control in a cast resin bushing:
1 shaft, 2 insulating body, 3 extended electrode, 4 flange
Bushings for rated voltages over 60 kV are usually built with capacitive voltage grading by intermediate electrodes. This is achieved by inserting metal foils inside the insulating material.

Potential distribution in cylindrical bushings
a) without intermediate electrodes, b) with intermediate electrodes (capacitor bushing)
Calculation of capacitive gradings

The insulation of a bushing is stressed radially and axially. All the boundary surfaces between the insulating material and the surrounding medium should be considered as a critical area.

The radial component $E_r$ can cause breakdown of the insulating material.

The axial component $E_a$ can under certain circumstances lead to surface discharges along the boundary surface.

Normally, the electric strength of the insulating material is appreciably higher than that of the boundary layer flashover, the axial stress is in general far more critical.
Calculation of Inception Voltage

The spacing of the layer is much smaller than the corresponding diameter, i.e. application of plane model of the electrode to calculate the inception voltage

The ac inception voltage for PD at the edge of the conductive layer

\[ V_i = K \left( \frac{S}{\varepsilon_r} \right)^{0.5} \]

\(V_i\) is in kV and \(s\) in cm. \(K\) value is related to the surrounding medium.
<table>
<thead>
<tr>
<th>Configuration</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal in air</td>
<td>8</td>
</tr>
<tr>
<td>Metal in SF$_6$</td>
<td>21</td>
</tr>
<tr>
<td>Metal or graphite edge in oil</td>
<td>30</td>
</tr>
<tr>
<td>Graphite edge in air</td>
<td>12</td>
</tr>
</tbody>
</table>

For optimum utilization of the dielectric it is recommended that the capacitive gradings be arranged so that the same partial voltage is across two adjacent layers, i.e.

$$\Delta V = \frac{V}{N}$$

where N is the total number of layers
Double side capacitive gradings

The layers are numbered from the central bolt \((n=0)\) to the flange \((n=N)\)

Let the spacing between the layers be

\[
S_n = r_n - r_{n-1}
\]
If the edge overlap $b_{ln}=b_{rn}$, a symmetrical bushing is obtained.
For different surrounding dielectrics bushings are required with different graded lengths on either side.
The main capacitance (hatched portion):

$$C_n = \frac{2\pi \varepsilon_0 \varepsilon_r a_n}{\ln(r_n / r_{n-1})}$$

All the capacitors are connected in series and they are equal to one another (because $\Delta V=\text{constant}$), i.e.

$$C_n = \text{const} = C$$
Grading in radial or axial direction?

• For radial grading, the radial field strength $E_r=\Delta V/s_n$ must be constant. This is satisfied for a constant layer spacing $s_n$.

• Assuming $C_{n+1}=C_n$, the recursion formula follows:

$$a_{n+1} = a_n \frac{\ln(r_{n+1} / r_n)}{\ln(r_n / r_{n-1})}$$

• For the plane approximation, with $s_n=r_n-r_{n-1}<<r_n$ we have

$$a_{n+1} \approx a_n \frac{r_{n-1}}{r_n}$$
• The recursion formulae permit the determination of the next layer from the data of the preceding one. The innermost radius $r_0$ is usually given; from the maximum permissible radial field strength $E_r$, the spacing $s_n$ is obtained from for a given voltage.

• If $a_0$ is also given, then all further data can be calculated. The resulting envelope of the layer edges is hyperbolic in shape for an asymmetrical bushing.
For axial grading, the axial field strength $E_a = \Delta V/b_n$ must be constant. The layer ends on each side must be displaced by the same length:

$$b_{ln} = const = b_l, \quad b_{rn} = const = b_r$$

For the length of the layer we have

$$a_{n+1} = a_n - b_l - b_r$$

From the assumption $C_{n+1} = C_n$ it follows

$$\ln\left(\frac{r_{n+1}}{r_n}\right) = \frac{a_{n+1}}{a_n} \ln\left(\frac{r_n}{r_{n-1}}\right)$$
The plane approximation yields:

\[ s_{n+1} \approx s_n \frac{a_{n+1}}{a_n} \cdot \frac{r_n}{r_{n-1}} \]

The dimensions of succeeding layers result from those of the preceding ones.

The flashover length \( L \) can be calculated approximately as \( L \approx N b_r \)
Procedure for Axial Grading Calculation

- Choice of the number of layers $N$ based on the experience that the voltage across two layers during ac test voltage $V_p$ shall be about 12kV.
- Choice of the flashover length $L$ from the condition that at $V_p$, the average field strength along the boundary surface must be limited.
- As a rule, the bolt radius $r_0$ and the total length $a_0$ are given. One then chooses an initial value of $r_1$ and continue to calculate with the recursion formula.
- Finally, one must make a few control calculations.
  - The highest radial field strength $E_r$ for the test voltage may not exceed the strength of the insulating material.
  - The highest permissible operating voltage must be distinctly less than $V_i$. 
Bushing for 110 kV transformer
1. connecting bolt
2. porcelain housing
3. hardboard body with double-sided capacitor grading
4. flange

Termination for 400 kV oil-filled cable
Objectives:

The design and construction of high voltage apparatus requires experience in the application of the laws of electric fields. The objectives of this excise is to design a 275 kV HV bushing using capacitive grading technique. The electric fields obtained in your designs require to be compared with modelling results.
HV bushing overall dimensions

- The dimensions given below are based on a real 275kV HV bushing.
- Inner diameter = 100 mm
- Outer diameter = 300 mm
- First foil length = 5000 mm
- N=21
- Foil thickness = 0.1 mm
- One end exposed to air and the other to oil
- Schematic drawing of the above HV bushing is shown in Figure 1.
Schematic diagram of 275 kV AC bushing (drawing not to scale)

Air end

Oil end

HV

2 mm

21 foils in total

2 mm

First foil length = 5 m

Al foil (100μm thick)

Flange (earthing)

Paper impregnated with oil

OD=30 cm

ID=10 cm
Insulation Design

Under ac conditions, double-sided capacitive gradings are typically required for HV bushings.

(a) Use either radial or axial grading to design the above bushing.
(b) Determine the electric fields at the interface
Field Modelling

You are required to do field modelling based on your two designs.

Both Opera2D and COMSOL Multiphysics software packages will be available for field modelling.

When you model the field distribution in the HV bushing, more emphasis should be placed on the interfaces and electrode edges.
Report (guide only)

• Abstract
• A brief review on field design in HV equipment
• Grading methods for dc and ac applications
• HV bushing and two capacitive grading methods
• Actual design details for 275kV AC bushing
• Electric field modelling
• Comparison and discussion (Suggestions on improvements)
• Conclusions
Assessment

• (i) Layout and presentation
• (ii) Content
• (iii) References and citations
• (iv) Individual contribution
Introduction to COMSOL
What is COMSOL

• Finite element analysis software package.

• Multiphysics field simulator.

• Contain several application-specific modules.
  including Electromagnetics
Why Modelling?

• Suppose the laws of physics were unknown

• Every idea must be tested... ...and tested
  ... and tested

• Trial and error: very expensive
Why Modelling?

Save money by
1 Describing the physics mathematically
2 Solving the mathematical problem

<table>
<thead>
<tr>
<th>PHYSICS SOLUTION</th>
<th>IDEA BY</th>
<th>FORMULA</th>
</tr>
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<tbody>
<tr>
<td>dynamics:</td>
<td>Newton:</td>
<td>F=m*a</td>
</tr>
<tr>
<td>mechanics:</td>
<td>Hooke:</td>
<td>F=k*s</td>
</tr>
<tr>
<td>gas/liquid flow</td>
<td>Bernoulli:</td>
<td>½ρv²+ρgh+p=c</td>
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<td>heat:</td>
<td>Fourier:</td>
<td>q=k(T-T_{ref})/L</td>
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<tr>
<td>current</td>
<td>Ohm:</td>
<td>V=I*R</td>
</tr>
<tr>
<td>electromagnetics</td>
<td>Maxwell:</td>
<td>a set of equations</td>
</tr>
</tbody>
</table>
Modelling

- Affordable
- Insights in what you can’t measure
- One model -> 1000 models
- All physics and chemical processes can be modelled
Why COMSOL?

• Lots of physics, lots of software
  – Elasticity
  – Air resistance
  – Electronics
  – Heat transfer
  – Chemical reactions
  – Electromagnetics
  – Abaqus, Ansys, Nastran etc
  – Fluent, CFX etc
  – Ansoft, Maxwell
  – Flowterm
  – Aspen
  – Opera

• COMSOL covers all
How Does COMSOL Work?

• Geometry -> create computer drawing
• Physics etc. -> laws of nature (\[ \nabla^2 V = -\frac{\rho}{\varepsilon \varepsilon_0} \])
• Meshing geometry -> to handle complex
  geometry together with the physics
• Solving -> Mathematical operations
• Postprocessing -> Viewing the results
Why Do People Simulate?

- Understand
- Verify
- Optimize
Example:
Electric Impedance Sensor
Introduction

- Electric impedance measurement techniques are used for imaging and detection
  - Geophysical imaging
  - Non-destructive testing
  - Medical imaging (Electrical Impedance Tomography)
- Applying voltage to an object or a matrix containing different materials and measuring the resulting potentials or current densities
- Frequency range: $1 \text{Hz} < f < 1 \text{GHz}$
Main points

• Use of Electromagnetics Module, Small Currents Application Mode
• Different Subdomains with different physical properties
• Logical expressions can be used to modify the geometry
• We will study how the lateral position of the air-filled cavity affects the measured impedance
Domain Equation

• Modelled with *Small In-Plane Currents* application in COMSOL Multiphysics
  – Valid for AC problems where inductive effects are negligible
  – The skin depth must be large compared to the object size

• Equation of continuity

\[
- \nabla \cdot \left( (\sigma + j\omega\varepsilon_r\varepsilon_0) \nabla V \right) = 0
\]

• Electric field

\[ E = - \nabla \cdot V \]

• Displacement

\[ D = \varepsilon_0 \varepsilon_r E \]
Equations and boundary conditions

\[ \mathbf{n} \cdot \mathbf{J} = J_n = 1 \text{A} \]

\[ \mathbf{n} \cdot \mathbf{J} = 0 \]

\[ -\nabla \cdot ((\sigma + j\omega \epsilon_r \epsilon_0) \nabla V) = 0 \]

\[ V = 0 \]
Results: Current distribution [on a dB scale]
Impedance defined as

\[
\frac{\text{voltage}}{\text{total current at electrode}}
\]
Results: Impedance phase angle
2D or 3D?

2D
- High numeric precision
- Easy drawing
- Quick results
- Resolve skin effect
- Resolve details - many individual turns

3D
- Full geometry
- Use 3D CAD
- "3D effects"
- 3D Visualization
- Homogenized coils / materials
- Demanding
- Difficult to resolve
- Complementary
Practical Issues

• Where in ECS can I find and use COMSOL Multiphysics?
  - Computing Lab (Level Three Zepler Bld)

• Can I install and use COMSOL Multiphysics at home?
  - No (Limited by license agreement)