The effect of material properties to electric field distribution in medium voltage underground cable accessories

Kenneth Väkeväinen

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EXAMENSARBETE	
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Sammandrag:

Arbetets syfte var att forska hur material egenskaperna påverkar elektriska fältets utspridning i mellanspänningsjordkabelprodukter. Avslutningar och skarvar är allmänna jordkabelprodukter och elektriska fältets utspridning spelar stor roll i hållbarheten och livslängden för dessa produkter. Grunderna om elektriska fältet och dess utspridning i mellanspännings kablar, -avslutningar och -skarvar forskades först i litteraturen. De kritiska delarna i en jordkabel avslutning och skarva definierades också genom litteraturen. Målsättningen var att hitta en optimal lösning för den nuvarande strukturen av värmekrympbara AHXAMK-W avslutningar och skarvar. Inga andra kabeltyper forskades i detta arbete för att strukturen i jordkablarna är allmänt liknande. Optimeringen utfördes genom att jämföra skillnader mellan åtta olika uppbyggnader för produkterna. Skillnaderna jämfördes med hjälp av en simuleringsmjukvara. Genom att ändra på relativa permittiviteten och konduktiviteten kunde påverkan av båda egenskaperna studeras. Mjukvaran som användes för simuleringarna var COMSOL Multiphysics. En tilläggs AC/DC modul användes för simulering av elektriska fältet. Simuleringsresultaten kontrollerades genom att utföra högspännings tester för jordkabelavslutningarna. Gamla test rapporter användes för att kontrollera simuleringsresultaten för jordkabelskarvarna. Användbarheten av simuleringsmjukvara i produktutveckling uppskattades också i detta arbete.

Nyckelord:	Ensto Finland Oy, mellanspänning, jordkabel, kabelavslutning, kabelskarv, elektriskt fält, simulation, COMSOL Multiphysics, högspänningstest, genomslag
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Abstract:
The purpose of this thesis was to study how material properties affect the electric field distribution in medium voltage underground cable accessories. A termination and a joint are two common types of products used with underground cables. The basics of the electric field and field distribution in underground cables and cable accessories were first studied through literature. The structure of terminations and joints and the critical parts in these products were also defined through literature. The aim was to find an optimal solution for the current structure of a heat shrinkable AHXAMK-W cable termination and joint. Cable accessories for other cable types were not studied since the general structure is similar in all products. The optimization was done by comparing the differences of eight material setups with the help of simulation software. The relative permittivity and conductivity of insulators were modified to study the seriousness of each property. The software that was used for the simulations was COMSOL Multiphysics. An additional AC/DC-Module was used to be able to simulate electric fields. Simulation reliability was verified based on high voltage tests and test results of previously tested products. The future use of simulation software in product development was also evaluated in this thesis.

Keywords:	Ensto Finland Oy, medium voltage, underground cable, cable termination, cable joint, electric field, simulation, COMSOL Multiphysics, high voltage test, breakthrough
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Tiivistelmä:
Tämän opinnäytetyön päämääränä oli tutkia materiaaliominaisuuksien vaikutusta sähkökentän jakautumiseen keskijännitemaakaapelituotteissa. Maakaapelipäätteet ja maakaapelijatkot ovat yleisesti maakaapeleiden kanssa käytettäviä varusteita. Sähkökenttää ja kentän jakautumista maakaapeleissa ja kaapelivarusteissa tutkittiin kirjallisuuden avulla. Maakaapelipäätteiden ja maakaapelijatkosten kriittiset alueet määriteltiin myös kirjallisuuden avulla. Tarkoituksena oli löytää paras mahdollinen ratkaisu AHXAMK-W kaapelin lämpökutistepäätteen ja -jatkoksen nykyiselle rakenteelle. Kaapelitarvikkeita muille kaapelityypeille ei tutkittu tässä työssä, sillä maakaapeleiden rakenne on yleisesti hyvin samantapainen. Tuotteiden optimointi toteutettiin vertailemalla kahdeksan erilaisen materiaali rakenteen omaavia tuotteita simulointiohjelmiston avulla. Suhteellista permittiviteettiä ja johtavuutta muuttamalla pystyttiin tutkimaan ominaisuuksien vaikutusta simulointitulokseen. Simulointiin käytetty ohjelmisto oli COMSOL Multiphysics johon oli lisätty AC/DC täydennys moduuli sähkökentän simulointeja varten. Simulointitulosten luotettavuus tarkistettiin suorittamalla korkeajännitekokeita maakaapelipäätteille ja tutkimalla vanhoja maakaapelijatkoille tehtyjen testien testiraportteja. Simulointiohjelmiston käytettävyyttä tuotekehitys tarkoitukseen arvioitiin myös tässä opinnäytetyössä.

Avainsanat:	Ensto Finland Oy, keskijännite, maakaapeli, maakaapeli pääte, maakaapeli jatkos, sähkökenttä, simulointi, COMSOL Multiphysics, suurjännitekoe, läpilyönti
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ABBREVIATIONS AND NOTATION

PD	Partial discharge
C	Coulomb, also capacitance
F	Force
q	Charge
ε_0	Vacuum permittivity
E	Electric field
ψ	Electric flux
J	Joule
ε	Permittivity
ε_r	Relative permittivity
δ	Loss angle of a dielectric
FEM	Finite element method
CSM	Charge simulation method
AC	Alternating current
DC	Direct current
CAD	Computer Aided Design
XLPE	Cross-linked polyethylene
PE	Polyethylene
LV	Low Voltage
MV	Medium Voltage
σ	Conductivity

FOREWORD

This engineering thesis was made for Ensto Finland Oy. I would like to thank everyone who participated in the project and made it possible for me to get it done. I would specially want to thank Kauko Alkila for giving me ideas to solve the problems in verification and optimization of underground cable accessories. I would also want to thank Anssi Aarnio for providing measurement data for material properties used in the simulations.

Porvoo, 29th October 2010

1 INTRODUCTION

Distribution of power has been a constantly improving branch ever since the invention of electricity. Efficient distribution of electricity requires higher voltages to be used. Choosing which voltage level to use is an economical issue. Higher voltages lead to a smaller current and therefore a smaller conductor cross section to transfer a certain amount of power. This lowers the cost of conductors and the losses caused by the current are also decreased. Higher voltages however increase the expenses for insulating structures. (Aro et al. 2003 p 14-16)

Distribution of power is generally implemented using overhead lines or underground cables. Underground cables are commonly used in low voltage and medium voltage solutions. The development of medium voltage underground cable accessories requires basic understanding of the stress caused by the electric field in different parts of the insulating structures. Material properties and product design play a key role in the durability of terminations and joints. The possibility to improve medium voltage cable accessories will be studied in this thesis.

1.1 Goal and methods

The purpose of this thesis was to study how different material properties affect the electric field distribution in medium voltage underground terminations and joints. The basics of electric force and field were first clarified by studying literature about the subject. Different methods for defining the electric field were also examined. The structure and critical parts in medium voltage underground cable accessories were defined through literature. The electric field in the critical area was studied using simulation software. The aim was to find an optimal solution for the current structure of the products and to determine the seriousness of two specific properties for insulators. The effect of relative permittivity and volume resistivity were studied. The optimization was done by comparing the differences of eight material setups. Simulation reliability was verified based on high voltage tests and test results of previously tested products. The future use of simulation software in product development was also evaluated in the thesis.

The seriousness of mounting faults in medium voltage underground terminations has been studied previously by Markus Hirvonen in his engineering thesis. The effects of common mounting faults were compared based on partial discharge measurements. The conclusion of Hirvonen's work was that the mounting faults related to the cutting point of the cable screening were most critical. Hirvonen's research supports the results from simulations and high voltage tests for the termination. (Hirvonen 2008)

Material properties of the non-metallic materials in medium voltage cable accessories have been studied by Anssi Aarnio in his master's thesis. Properties like relative permittivity, volume resistivity and breakdown voltage were measured. The permittivity was measured using an IDA 200 Insulation Diagnostic System. An electrometer was used for measuring volume resistivity. Aarnio's measurement results have been used for some of the materials in the electric field simulations. (Aarnio 2010)

1.2 Definition

The aim of the thesis was to improve the behavior of the electric field in a medium voltage termination and a joint. The optimization of these products was done using a simulation software called COMSOL Multiphysics. No other simulation software was used.

Relative permittivity is a not a constant and can vary depending on voltage, frequency and other parameters. The non-linearity of relative permittivity has however not been taken into consideration in the simulations and the values are assumed to be constants.

The underground cable accessories that are examined in this thesis are Ensto's heat shrinkable cable accessories for AHXAMK-W cables. Cable accessories for other cable types were not studied since the general structure is similar in all products. The use of a polymeric insulated cable was chosen because they are more common today than paper insulated cables and other cable types.

2 ELECTRIC FORCE AND FIELD

Ordinary matter is made from electrons, protons and neutrons. Electric charge is an intrinsic property of electrons and protons. The charge can be either positive or negative. The total charge of an object is the sum of its constituent charges. Similar charges are repulsive and opposite charges attractive. All electrons and protons carry the same charge. The magnitude of an electron's charge is exactly the same as a proton's, but with an opposite sign. The magnitude of a positive or negative charge is known as the elementary charge, e. (Wolfson 2007 p. 328-329)

The SI unit of charge is the coulomb, C. The coulomb is used to define electric current but it can also be described as about 6.25 x 1018 elementary charges. The repulsion and attraction of electric charges create an electric field that implies a force. The strength of the force between two charges can be examined with Coulomb's law. Coulomb's law states that the force between two point charges act along the line joining them. The magnitude of the force is proportional to the product of the charges and inversely proportional to the square of the distance between them. (Wolfson 2007 p. 329-330)

$$F = \frac{k\, q_1 q_2}{r^2} \qquad \text{(Coulomb's law)} \qquad (1)$$

The magnitude of the force between charges q_1 and q_2 is given by equation 1, where r is the magnitude between the two charges and k is a proportionality constant known as Coulomb's constant. The SI value of k is approximately 9.0 x 10^9 Nm^2/C^2 as shown in equation 2. With the help of Coulomb's law we can calculate the electric field strength at a given point. (Wolfson 2007 p. 330-331)

$$k = \frac{1}{4\pi\varepsilon_0} \approx 9.0 * 10^9 \frac{Nm^2}{C^2} \qquad (2)$$

The constant ε_0 in equation 2 is the so called dielectric constant. It is also known as vacuum permittivity. The SI value of ε_0 is 8.85 * 10^{-12} F/m. (Wolfson 2007 p. 351)

The electric field is defined as the force per unit charge that would be experienced by a point charge at a given point. (Wolfson 2007 p. 332)

$$E = \frac{F}{q} \tag{3}$$

The electric field is a continuous entity that can be represented using vectors. Vectors are drawn as extended arrows which represent the field at the end of the vector. When using vectors to represent the field it's good to note that we can't draw them all. The field still exists at every point in space even if we can't draw a vector everywhere. (Wolfson 2007 p. 332-333)

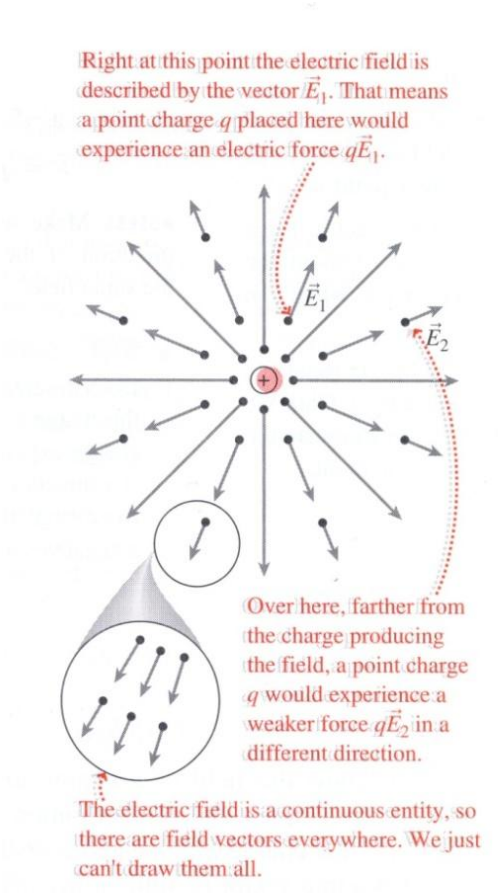


Figure 1. Electric field represented as vectors (Wolfson 2007 p. 333)

A more practical way to visualize electric fields than using vectors is to use electric field lines. Field lines are continuous lines whose direction is everywhere the same as that of the electric field. Field lines begin on positive charges and either end on a negative charges or extend to infinity. (Wolfson 2007 p. 347)

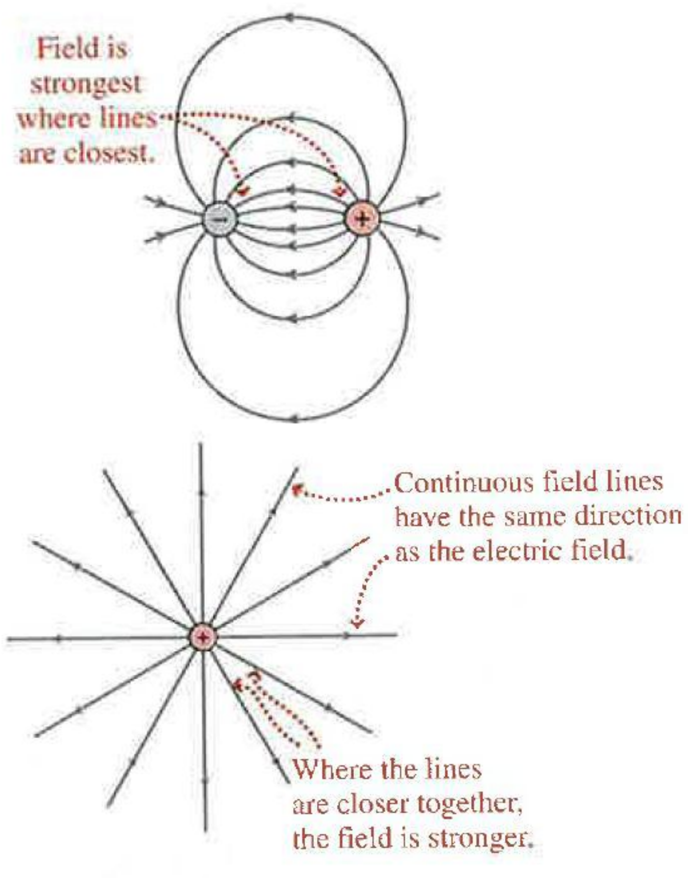


Figure 2. Field lines used to visualize the electric field (Wolfson 2007 p. 348)

With the help of Coulomb's law we can conclude that the field is stronger where the lines are closer to the charge and weaker when they are farther apart. This allows us to study the field's relative magnitude and direction from field line pictures. (Wolfson 2007 p. 348)

The electric field of a charge distribution ultimately consists of point like electrons and protons but it's convenient to approximate that charge is spread continuously over a volume, a surface or a line. The charge distribution is described as volume charge density ρ (C/m^3) when it extends throughout a volume. Charge distributions over surfaces and lines are described as surface charge density σ (C/m^2) and line charge density λ (C/m). (Wolfson 2007 p. 334-336)

Calculating the electric field of certain charge distributions can be easier using Gauss's law. Gauss's law is equivalent with Coulomb's law and states that the electric flux through any closed surface is proportional to the enclosed electric charge. (Wolfson 2007 p. 351)

$$\psi = \oint E * dA = \frac{q}{\varepsilon_0} \quad \text{(Gauss's law)} \qquad (4)$$

The electric flux ψ and electric field E are related but distinct quantities. The electric field is a vector defined at each point in space. The flux instead is a scalar and a global property which describes how the field behaves over an extended surface rather than at a single point. (Wolfson 2007 p. 350)

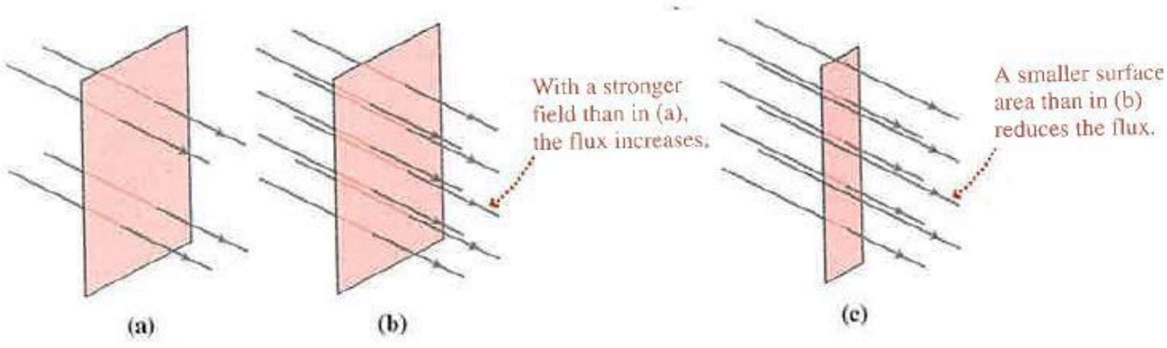


Figure 3. Electric flux through flat surfaces (Wolfson 2007 p. 350)

2.1 Electric potential

The electric field is defined as the force a charge would experienced at a given point. The work done in moving a charge against this force is stored as potential energy. Electric potential is the energy per unit charge and the electric field measures the rate of change of potential. Electric potential is used to define the difference in energy between two points. The units describing potential difference are joules per coulomb, *J/C*. The unit is however important enough to have its own name the volt, *V*. Potential difference in a uniform electric field varies linearly with distance. The linearity allows us to draw potential differences using equipotential lines, where the different between each line is equal. Equipotential lines are always perpendicular with electric field lines. If we know the electric field lines, we can construct equipotential lines, or vice versa. Specifying the potential at each point thereby gives us all the information needed to determine the electric field. (Wolfson 2007 p. 367-379)

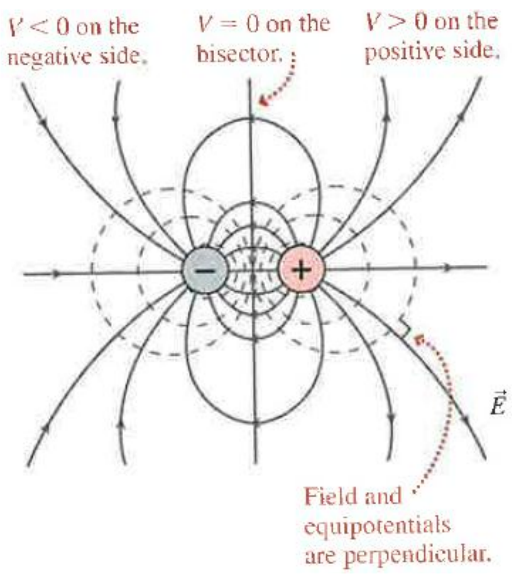


Figure 4. Electric field and equipotential lines for a dipole (Wolfson 2007 p.376)

2.2 Matter in electric fields

Electric fields applied over matter gives rise to forces on charged particles within the matter. Since bulk matter contains huge amounts of point charges the behavior of matter is to some extent determined by electric fields. Materials can be divided into conductors and insulators, depending on how they behave in an electric field. Conductors are materials where individual charges are free to move throughout the material. Materials in which charge is not free to move are called insulators or even dielectrics. (Wolfson 2007 p. 338-341)

2.2.1 Conductor in an electric field

When an electric field is applied over a conductor the free charges move in the direction of the field or opposite depending whether they are positive or negative. The movement of charges increases the internal field until its magnitude equals that of the applied electric field. At this point the conductor is at electrostatic equilibrium and charges within the conductor experience zero net force. The internal and applied fields are equal but opposite when equilibrium is reached. This also means that the electric field inside a conductor is zero when the conductor is at electrostatic equilibrium. (Wolfson 2007 p. 359)

The repulsion of equal charges forces the charges to move on the surface of a charged conductor. Since there can't be an electric field inside a conductor the field must also be on the surface of the conductor. The field at the surface of the conductor is perpendicular to the surface and can be calculated with the help of Gauss's law. (Wolfson 2007 p. 359-362)

$$E = \frac{\sigma}{\varepsilon_0} \tag{5}$$

2.2.2 Insulator in an electric field

Insulators contain charges that are bound into neutral molecules and thereby electric current can't flow through. Materials where the applied electric field causes stretching or rotation of molecules are called dielectrics. The application of an electric field over a dielectric results in the alignment of molecular dipoles with the field. The fields of the dipoles then reduce the applied electric field within the dielectric. (Wolfson 2007 p. 340-341)

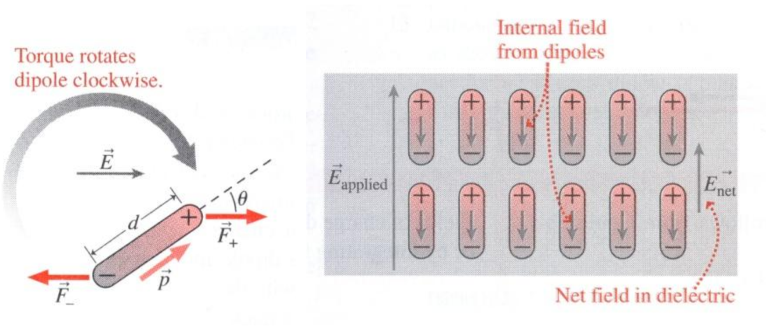


Figure 5. Alignment of molecular dipoles in an electric field (Wolfson 2007 p.339 & 341)

The alignment of molecules is called polarization. The direction of the polarization changes when an alternating current is used. The polarization causes constant movement of molecules that heats the dielectric as a result of friction. (Aro et al. 2003 p. 49-51)

The ability of a material to polarize in an electric field can be described with a property called permittivity. Permittivity is a measure of how an electric field decreases in a dielectric. The permittivity of an insulator is called ε. Relative permittivity ε_r is more commonly used as it describes the relation between the permittivity of the insulator and the permittivity of vacuum. (Aro et al. 2003 p.20-21)

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{6}$$

Dielectric loses are generated in the insulator when it is placed in an alternating electric field. The losses are a result of the constant movement of the molecules and the friction caused by the movement. An insulator is never completely ideal but instead it contains a bit of conductivity. The conductivity of an insulator generally increases when it heats up, which also increases the dielectric losses. (Aro et al. 2003 p. 49-51)

Dielectric losses of an insulator are described as an angle δ, which describes how much the insulator differs from an ideal insulator. A higher angle means that the material is more conductive which means more heating as a result of the current flowing through the insulation. (Aro et al. 2003 p. 51-53)

If the electric field applied to a dielectric is too great the heating affects the material so that it starts to act as a conductor. This phenomenon is called dielectric breakdown and can cause severe damage in electric equipment. (Wolfson 2007 p. 341)

3 DEFINING THE ELECTRIC FIELD

When optimizing insulators it is essential to know how the electric field is divided inside the insulating structures and to localize critical field peaks. There are many different ways to define the electric field in an insulating structure. (Aro et al. 2003 p. 31)

An analytic calculation method can be used in some simple cases. The electric field is generally too complex in common insulation structures for this method to be used but in some specific occasions the electric field can easily be defined by calculation. One common structure which can easily be calculated is the cylindrical capacitor. A cable is a good example of a cylindrical capacitor. (Aro et al. 2003 p. 31-38)

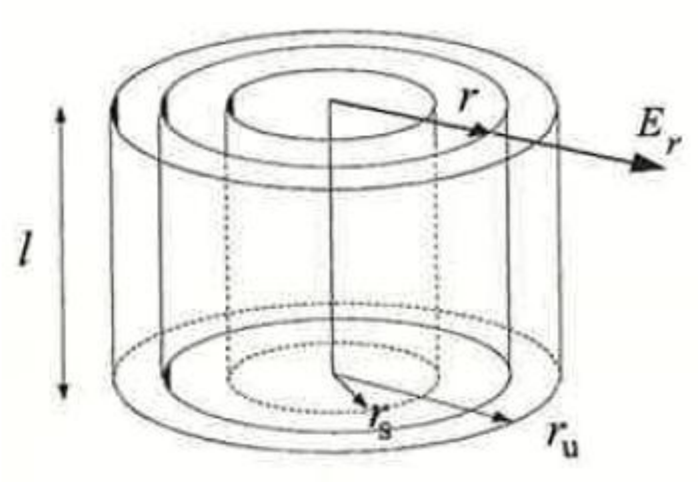


Figure 6. Cylindrical capacitor (Aro et al. 2003 p. 35)

Simple two dimensional structures can be defined graphically using a so called orthogonal field graph. The graph is usually generated by first drawing the equipotential lines and thereafter the flux lines. The drawing can be checked using a simple circle method. Graphical field graphs do not give accurate results but can be used for fast sketching of field forms. (Aro et al. 2003 p. 39-40)

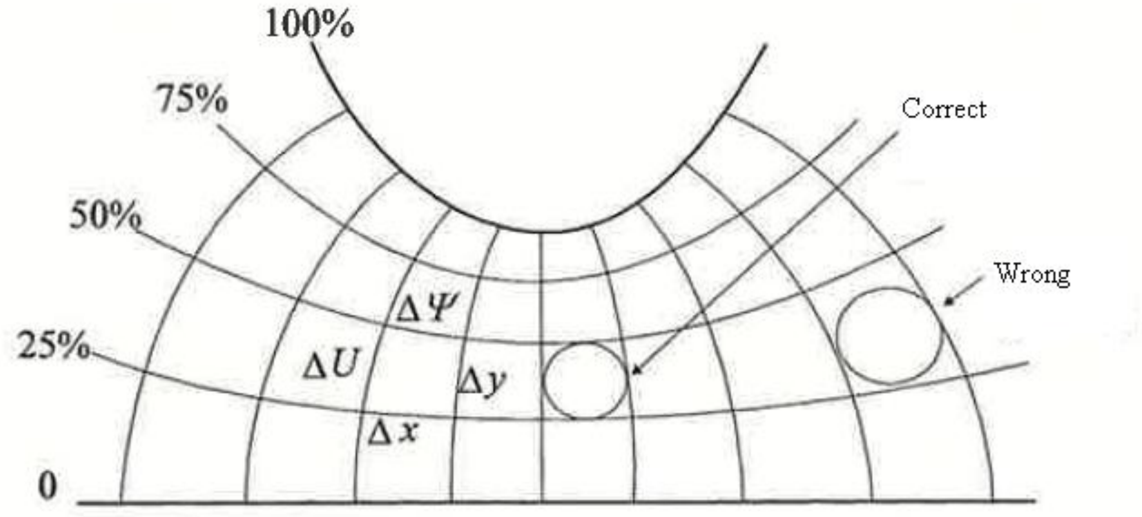


Figure 7. Orthogonal field graph (Aro et al. 2003 p. 39)

Numerical solving of electric fields is the most common method used today. Static 2D and axially symmetric fields can be solved with great accuracy using different numerical methods. More inaccurate methods have to be used with 3D models but the development on the field is strong. The most common numerical methods used are finite element method, FEM and charge simulation method, CSM. (Aro et al. 2003 p. 42)

The calculation of electric fields is based on solving Poisson's and Laplace's equations. Field strength, electric flux and potential differences are calculated at each point of the examined area. This is possible only if there is enough information of boundary conditions within the examined structure. (Aro et al. 2003 p. 42)

Finite element method is originally used in strength theory but it can be used to define different kind of fields. The basic idea of FEM is to divide the examined area to small elements where each field's magnitude is described by a function. (Aro et al. 2003 p. 43)

The potential v is used as field magnitude when static electric fields are examined. To minimize solving times the field strength inside the element is assumed to be constant. In highly non-homogeneous fields this assumption can lead to inaccurate results. Calculation accuracy can easily be improved by making the element net denser. This increases the amount of calculations and cannot be done unlimitedly. (Aro et al. 2003 p. 44-47)

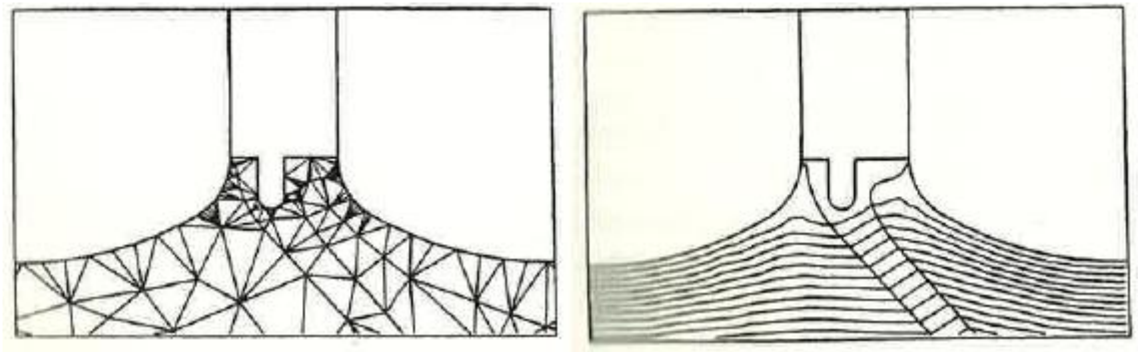


Figure 8. FEM used to calculate an electric field (Aro et al. 2003 p. 47)

3.1 Comsol Multiphysics

COMSOL Multiphysics is a simulation software package that uses finite element method. The software has predefined modeling interfaces from fluid flow and heat transfer to structural mechanics and electromagnetic analyses. The software can be extended with add-on modules that offer increased usability within different physical interfaces. (COMSOL)

COMSOL was started by a group of graduating students encouraged by their professor Germund Dahlquist at the Royal Institute of Technology in Stockholm. The software formerly known as FEMLAB was a PDE toolbox for MATLAB which was based on codes that Dahlquist had developed for a graduate course. (Obituary: Germund Dahlquist)

3.1.1 AC/DC Module

The AC/DC module makes simulation and modeling of resistors, capacitors, inductors, coils, motors and sensors possible. The electric properties of these devices are influenced by different kinds of physics that need to be understood during a products design process. The functionality of the AC/DC Module is designed for the needs of electrical and electromechanical engineers and the capabilities of the add-on cover electrostatic, magnetostatic, low frequency and electromagnetic phenomena. (AC/DC Module)

3.1.2 CAD Import Module

The CAD Import Module allows users to import all major CAD formats directly into the COMSOL Desktop for simulation of accurate designs. The add-on includes the Parasolid geometry kernel with repair and defeaturing tools. These tools allow the user to repair and remove unnecessary details from imported CAD geometries, assuring that the geometries are mathematically correct for simulation. (CAD Import Module)

4 MEDIUM VOLTAGE UNDERGROUND CABLES

Power cables are divided into three groups: low voltage, medium voltage and high voltage. Low voltage cable solutions are rated from 300/500 V to 600/1000 V, medium voltage from 1.8/3 kV to 20.8/36 kV and cable solutions greater than 20.8/36 kV are called high voltage. Underground cables are common in low voltage and medium voltage solutions. (Aarnio 2010 p. 3)

4.1 Structure and materials

Cable structure varies in different medium voltage cables but the cable usually consists of a conductor, conductor screen, insulation, insulation screen, shield and outer sheath. (Elovaara & Laiho 1988 p. 373)

The conductor of a medium voltage cable is mostly made of copper or aluminum. Copper has better conductivity but the lightness and the price of aluminum has made it the most common conductor material, especially in bigger cross-sections. (Elovaara & Laiho 1988 p. 373)

The conductor is covered with a semiconducting screen that evens out the surface of the conductor and thereby also decreases peaks in field strength. The screen also reduces thermal stress directed to the insulation in fault situations. (Elovaara & Laiho 1988 p. 373-374)

Next to the conductor screen is the insulation of the cable. Different types of plastics have become more and more common as insulation materials but also oil impregnated paper and rubber is used. The purpose of the insulation is to provide sufficient dielectric strength to the cable and to effetely transfer the heat generated in the conductor out from the cable. (Elovaara & Laiho 1988 p. 374)

The insulation is covered with a semi-conducting screen. The screen is made of conducting metal ribbons or semiconducting material. The insulation screen together with the conductor screen limits the electric field between two cylindrical surfaces. (Elovaara & Laiho 1988 p. 374)

On top of the insulation screen is the cable shield. The shield works as a protective layer for fault currents and it decreases interferences caused by the cable. The structure of the shield depends on the cable type and the purpose of use. The shield can be either shared or individual for each phase. Different shield materials are lead, aluminum and copper. (Elovaara & Laiho 1988 p. 375)

The final layer of a cable is the outer sheath. Sheath can be made of metal, plastic or rubber. Lead and aluminum are used in metal sheathed cables and PE, PEX and PVC in plastic sheaths. (Elovaara & Laiho 1988 p. 375)

4.1.1 AHXAMK-W cable

AHXAMK-W is a cross-linked polyethylene (XLPE) insulated medium voltage cable with an aluminum tape shield. The conductor material is aluminum and the outer sheath is made of polyethylene (PE). AHXAMK-W is a three phase cable but only one phase was and used in simulations and testing.

A simplified structure of AHXAMK-W was used in the simulations. The cable used in tests was Reka's 185 mm^2 AHXAMK-W 24 kV.

Figure 9. Pie figure of AHXAMK-W (Reka Kaapeli)

AHXAMK-W cable construction:

1. Conductor. Longitudinally watertight stranded aluminum.
2. Conductor screen. Extruded semiconducting compound.
3. Insulation. Extruded XLPE compound.
4. Insulation screen. Extruded semiconducting compound.
5. Bedding. Semiconducting water blocking tapes.
6. Aluminum tape shield. Aluminum foil laminate, works also as radial water barrier.
7. Outer sheath. Extruded PE.

(Reka Kaapeli)

5 MEDIUM VOLTAGE UNDERGROUND ACCESSORY

Different accessories are needed when new underground networks are built and old ones are repaired. Terminations and joints are two common products used with underground cables.

5.1 Terminations

Figure 10. Medium voltage underground cable termination (Training Module: Ensto Underground Solutions)

The purpose of a cable termination is to connect an insulated cable to a circuit. The termination also protects the cable mechanically, keeps moisture out form the cable and helps to keep the oil inside an oil impregnated paper cable. The structure of a cable termination depends on cable type, used voltage and installation environment. For example terminations used outside must be mechanically strong and completely waterproof. (Elovaara & Laiho 1988 p. 380-381)

The cable termination must withstand the same electric stress that the cable does. It is important to note that the electric field rises remarkably at the end of the screening and some sort of grading is required. There are different techniques for implementing the grading. Geometric grading can be implemented by adding a cone-shaped (stress cone) insulation on top of the cable insulation and the end of the screening. Another solution is to add a shaped layer of insulation with a different permittivity than the surrounding insulation on top of the cutting point of the screening (epsilon control). An alternative solution is to add a flat layer with a high permittivity on top of the screening and the insulation (refractive stress control). The capacitance between the screening and the peeled insulation increases as a result of the high permittivity and the electric field is divided more smoothly outside the insulating structures. (Aro et. al. 2003 p. 154-156)

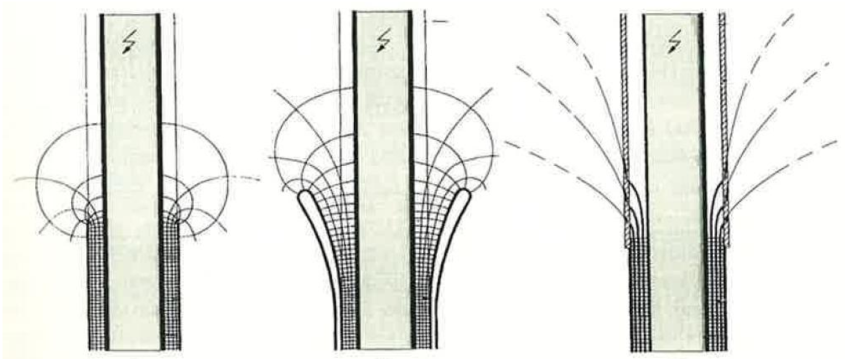


Figure 11. Voltage divisions in a cable termination without grading and examples of stress cone and refractive stress control (Aro et. al. 2003 p. 155)

5.1.1 HITW1.2403L

The cable termination examined in this thesis was a HITW1.2403L heat shrink termination. The product card of the termination describes it as following:

> "The termination kit is used for indoor terminating of max. 24 kV cables with XLPE insulation, aluminum tape shield and plastic outer sheath. The kit is suitable for AHXAMK-W cables containing the components for three cores."

Figure 12. Content of HITW1.2403L heat shrink termination kit (HITW1.2403L product card)

HITW1.2403L heat shrink termination kit includes following materials:

- Medium voltage shear head bolt cable lug
- Stress control tube
- Non-tracking tube
- Rain shed
- Stress control tape
- Sealing mastic
- Grey sealing mastic for screw holes
- Self bonding insulating tape
- Tinned copper braid with LV cable lug
- LV shear head bolt lug
- Constant force spring
- Installation accessory like tape, peeling rope, grinding paper and cleaning tissue. (HITW1.24 product card)

The key features of installing a HITW1.24 termination are described below, more specific instructions can be found in appendix 1.

The installation of a termination is started by preparing a cable according to the installation instructions. A medium voltage cable lug is installed on the end of the conductor. A stress control mass is stretched on top of the cutting point of the screening. The stress control mass smoothen the surface between the insulation and the tube on top of it and therefore prevents air bubbles from being left inside the termination. A shrinkable stress control tube is shrunk on top of the stress control mass and the cable insulation. The stress control tube together with the mass take care of the grading. An anti-tracking tube is shrunk on top of the stress control tube to prevent leakage currents that flow on the surface of the termination from destroying the cable insulation.

5.2 Joints

Figure 13. Medium voltage underground cable joint (Training Module: Ensto Underground Solutions)

The purpose of a cable joint is to connect two cables together. Cable joints are also needed when cable faults are repaired. (Elovaara & Laiho 1988 p. 381)

The conductors are usually connected together with a connector that can be welded, pressed or tightened by a screw. The connector surface must be smooth and cylindrical to improve the electric field in the joint and to prevent electric field peaks from being generated. The surface can also be smoothened by adding a semiconducting layer on top of the connector. It's especially important to use a big radius in the ends of the connector to ensure that peaks in the electric field do not compromise the insulation. The insulation material of a joint depends on what types of cables are used. Different materials like plastics, tapes, paper ribbons, cable mass or cable oil can be used. The insulation screening can be implemented for example with copper gauze. The insulation and the screening are covered with a sheath that protects the joint from mechanical stress. The sheath can be made of plastic or metal depending on the surrounding environment. (Elovaara & Laiho 1988 p.381-384)

5.2.1 HJW11.2403C

The cable joint examined in this thesis was a HJW11.2403C heat shrink joint. The product card of the termination describes it as following:

> "The joint kit is used for jointing of max. 24 kV cables with XLPE insulation and aluminum shield. The kit is suitable for AHXAMK-W cables, containing the components for three cores."

Figure 14. Content of HJW11.2403C heat shrink joint kit (HJW11.2403C product card)

HJW11.2403C heat shrink joint kit includes following materials:

- Medium voltage shear head bolt connector
- Stress control tube
- Insulating and semiconducting tube
- Sealing tube
- Stress control tape
- Sealing mastic
- Gray sealing mastic for screw holes
- LV connector
- Tinned copper braid
- Constant force spring
- Self bonding insulating tape
- Installation accessory like tape, peeling rope, grinding paper and cleaning tissue. (HJW11.2403C product card)

The key features of installing a HJW11.24 joint are described below, more specific instructions can be found in appendix 2.

The structure of a joint consists of two cables prepared as in a termination and a medium voltage connector that connects the cables together. A stress control mass is stretched on top of the connector body and at the cutting point of the screening in both cables. The stress control mass smoothen the surface between the connector and the tube on top of it and prevents air bubbles from being left inside the joint. A shrinkable two layer stress control tube is shrunk on top of the connector and all the way over the cutting point of the screening in both cables. The inner layer of the stress control tube is similar than the stress control tube of a termination but with a slightly lower permittivity. The outer layer of the stress control tube is insulating. Another tube with insulating and semi-conductive layers is shrunk on top of the stress control tube. The inner layer of the second tube is insulating and the outer is semi-conductive. The semi-conductive layer is used to prevent electric field peaks from generating at the surface of the copper gauze that is used as a grounding electrode. On top of the copper gauze is a sealing tube that keeps water out from the joint and provides the mechanical protection that is needed.

6 ELECTRIC FIELD SIMULATION OF MEDIUM VOLTAGE ACCESSORY

The aim of the thesis was to optimize the electric field distribution in medium voltage underground accessory. The optimization was done by changing material properties in the termination and the joint. Different material setups were compared using COMSOL Multiphysics to find out the seriousness of each material property.

3D models of a termination and a joint were made to be able to perform the simulations. The models were made by Peter Kaario from Plasticity with Pro/Engineer. The dimensions for the models were made according to installation instructions. A real termination and a joint were also built and then cut in half to better represent the shapes inside an installed product.

The structure in the 3D models was too complex so they could not be used in COMSOL Multiphysics. COMSOL's personnel proposed to start modeling in 2D mode before going on with the 3D models. 2D axial symmetry mode was best fitting for the symmetric conductors and accessories. The 2D simulations offered enough information for the study so the 3D models were only used for generating the 2D models.

6.1 Defining the product baseline

The simulations were done in 2D axial symmetry mode. The 2D models were generated from the 3D files and simplified so that they were axially symmetric. The simplification only concerned the cable lug in the termination and the connector in the joint. The shape of the cable lug and the connector was assumed to be symmetric without any screw holes or screws. The non-symmetric shape of the connector can greatly decrease the durability in the current structure of the joint. The axially symmetric model is drawn from the center of the conductor outwards to the right side of the Y-axis. A layer of air was added to the model of the termination to better simulate the real situation. No such layer is needed in the model of the joint since only the electric field inside the joint is examined.

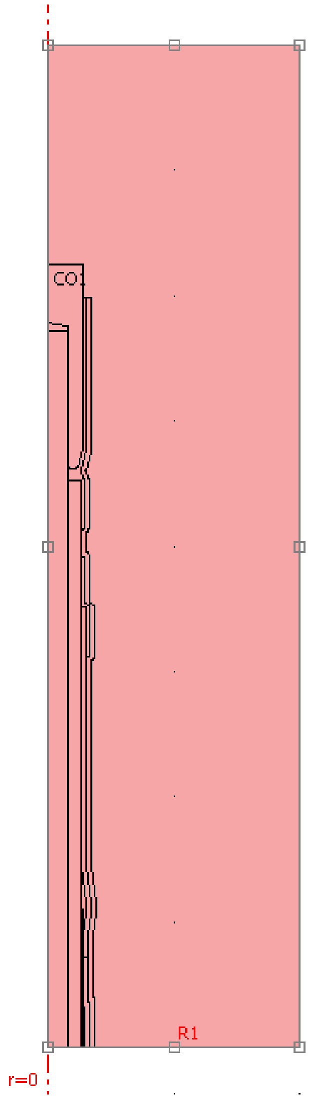


Figure 15. 2D model of axially symmetric simplified termination

Subdomain settings and boundary conditions need to be specified after importing a model. The electric properties of all layers or groups are specified in subdomain settings. Conductivity σ and relative permittivity ε_r need to be specified for each material that is used in the simulation.

The conductivity of a material is the inverse of electric resistivity which is a more commonly specified value for insulating materials. The SI unit for conductivity is siemens per meter (S/m). (Electrical conductivity)

$$\sigma = \frac{1}{\rho} \tag{7}$$

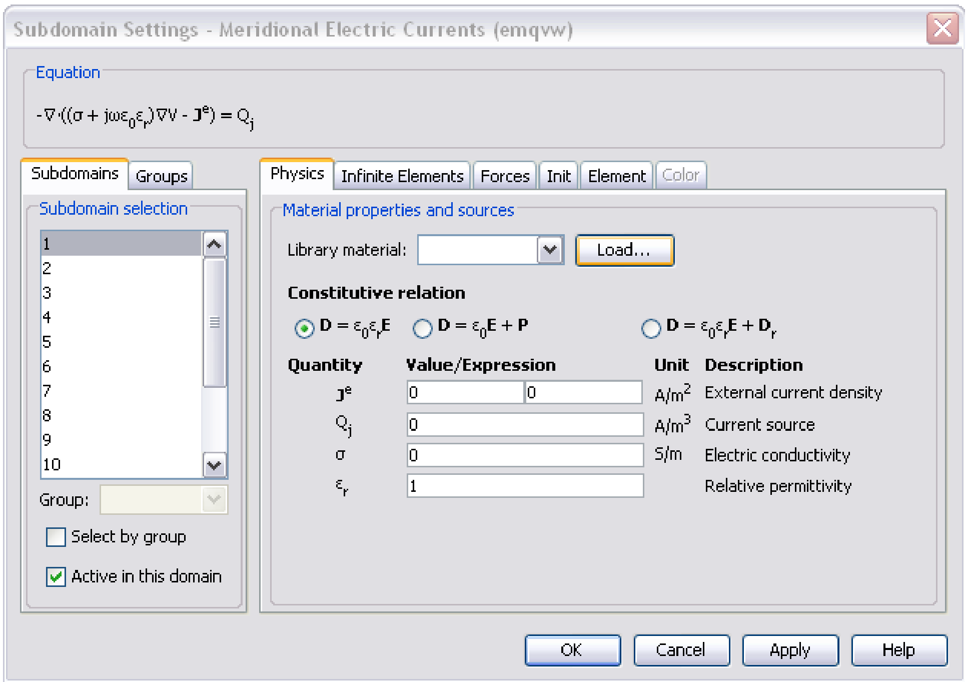


Figure 16. Subdomain settings

Boundary conditions need to be set up after specifying the materials. All boundaries lying on the Y-axis need to be set as axial symmetry. All internal layers are chosen as continuity and the outer edges as electric insulation. The conductor is set as electric potential and the aluminum screen of the cable as ground on the X-axis.

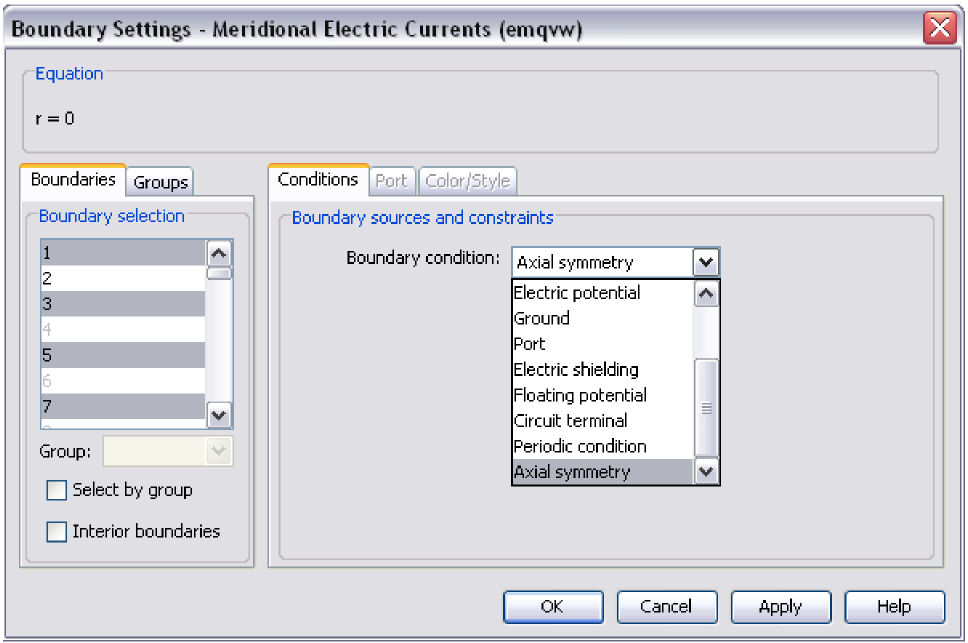


Figure 17. Boundary settings

After setting up materials and boundaries it is time to generate the mesh for the model. There are various possibilities when generating a mesh. It is important to always use the same element net when comparing how changes made in subdomain and boundary settings affect the results.

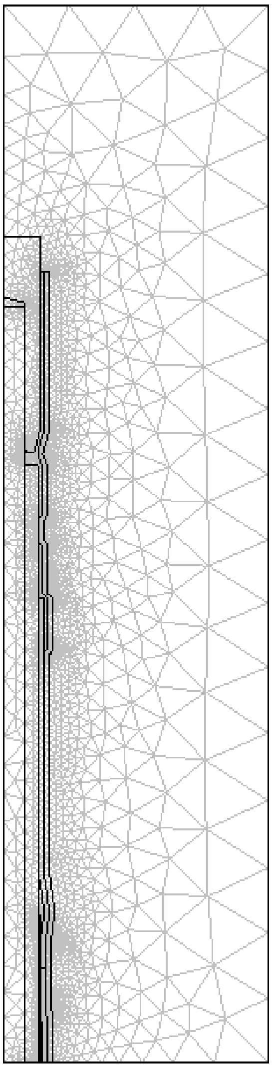


Figure 18. Meshed model of termination

The final thing to do after generating the mesh is to solve the simulation. The result is presented as a colored surface model with the electric potential as the default property. Various post processing tools can be used for analyzing results of different properties. A line plot is an excellent tool when studying changes in potential difference or electric field. The line plot tool is used to draw graphs showing how a property changes along a straight line.

6.1.1 Material properties

COMSOL has a material library with some predefined values for basic materials that can be used in most physic modeling environments. The AC/DC module also comes with some specific materials that are more commonly used in electronic equipment.

A material library of the materials used in medium voltage cables and accessories had to be done before the actual simulation could be started. The electric properties used in the simulations are chosen according to different manufacturer specifications and measurements done by Anssi Aarnio in his Master's Thesis.

The properties for copper, aluminum and air were used from the predefined material libraries. The conductivity of air was null according to the predefined values. A value of 1e-20 was used to prevent problems in calculations.

Properties for the plastics in cable insulation and screening were obtained from Borealis' datasheets. The materials are commonly used plastics in medium voltage cables. The properties for the cable insulation are according to specifications for LE4201R. The properties for the cable screening are according to Visico™ LE0540 and the cable outer sheath according to Borstar® HE6062.

Table 1. Electric properties of plastics used in MV cables

Material	Volume resistivity [Ωm]	Conductivity [σ]	Permittivity [εr]
Cable insulation	1.00E+14	1.00E-14	2.3
Cable screening	1.00E+00	1	1
Cable outer sheat	1.00E+14	1.00E-14	2.2

The properties for the tubes and masses used in the termination are according to manufacturer specifications. The manufacturer has not specified a relative permittivity for the non-tracking tube or the sealing mastic so these values were chosen according to the measurements done by Aarnio. The permittivity values mentioned in Aarnio's thesis are measured with 140 V at 1000 Hz (Aarnio 2010 p. 69-71). The values used in the simulations are according to measurements done with 140 V at 50 Hz.

Table 2. Electric properties of materials used in model of termination

Material	Volume resistivity [Ωm]	Conductivity [σ]	Permittivity [εr]
Non-tracking tube	1.00E+11	1.00E-11	3.4
Stress control tube	1.00E+07	1.00E-07	35
Stress control mastic	1.00E+08	1.00E-08	15
Sealing mastic	1.00E+10	1.00E-10	3.31

Manufacturer specifications were used in the simulation of the joint for all the properties that had a value specified. The missing values are according to Aarnio's measurements. The stress control tube and the insulating and semiconducting tube are both two-layer tubes which caused problems in measurements. Aarnio could however identify the materials used in these layers. The inner layer of the stress control tube is similar as the stress control tube used in terminations and the outer layer is the same as an insulating tube. The inner layer of the insulating and semiconducting tube is also the same insulating tube and the outer layer is same as a semiconducting tube.

Table 3. Electric properties of materials used in model of joint

Material	Volume resistivity [Ωm]	Conductivity [σ]	Permittivity [εr]
Stress control mastic	1.00E+08	1.00E-08	15
Stress control tube, inner layer	1.00E+10	1.00E-10	30
Stress control tube, outer layer	1.00E+11	1.00E-11	3.5
Insulating / semiconductive tube, inner layer	1.00E+10	1.00E-10	3.5
Insulating / semiconductive tube, outer layer	1.00E+03	1.00E-03	1
Sealing mastic	1.00E+08	1.00E-08	4.26
Sealing tube	1.00E+12	1.00E-12	3

6.2 Simulation of a HITW1.24 termination

The point of interest in terms of electric field in a medium voltage termination is the cutting point of the cable screening. At this point the electric field rises rapidly when the conductor and the grounding electrode diverge. The structure of a termination at the cutting point can be examined in figure 19. The shining layer on the left is the conductor. On top of the conductor are the cable insulation and screenings. The yellow layer is the stress control mass. The cutting point of the insulation screening can be seen inside this layer. The black layer on top of the mass is the stress control tube and the red layer above it is the anti-tracking tube.

Figure 19. Cutting point of the cable screening

The material properties used in the simulation are according to the values in table 1 and table 2. The electric potential in the conductor is set as 12 kV. The mesh for the model was created using default meshing settings with one refining of the mesh. The electric field strength is displayed on the surface of the model in a color scale and the equipotential lines as contours. The electric field peak can be seen as a red dot at the cutting point of the cable screening in figure 19.

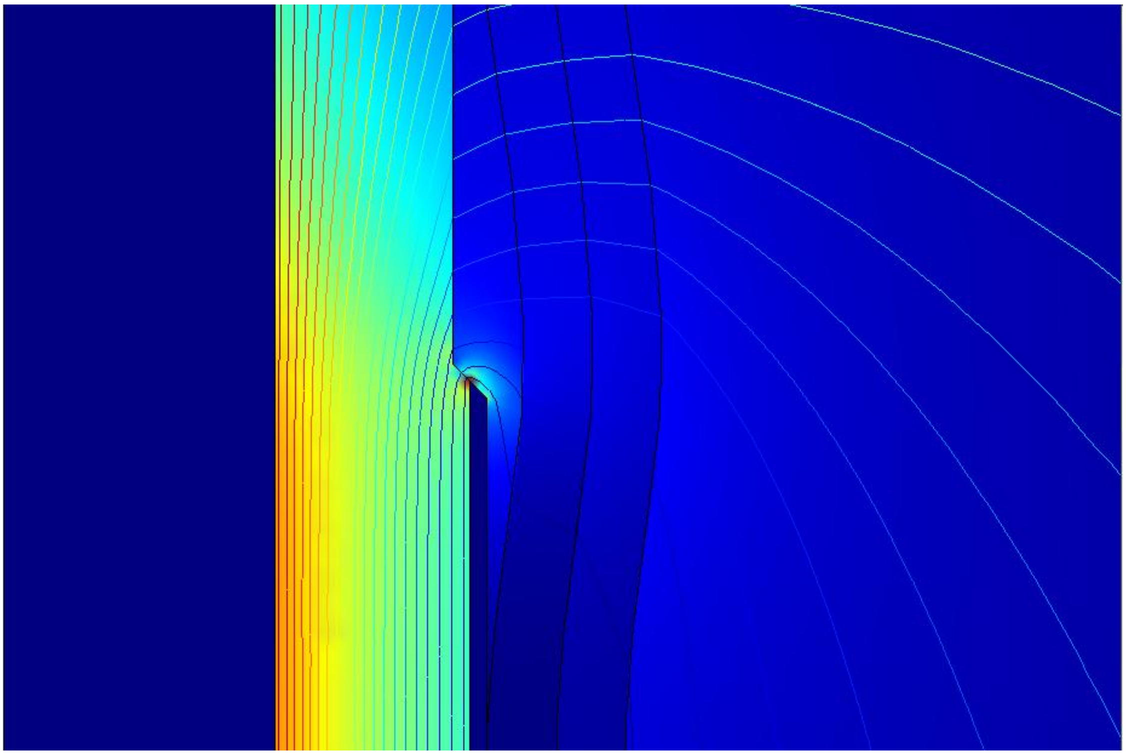


Figure 20. Electric field and equipotential lines in HITW1.24 termination

The surface plot illustrates clearly how the stress control mastic and the stress control tube force the electric field towards the conductor and the stress from the field is mainly divided within the conductor insulation. When the electric field is controlled like this the stress at the cutting point of the screening becomes much smaller. The shape of the electric field can be seen from the equipotential lines. The distance between the lines is much denser inside the insulation than in the stress control components and therefore the field is also much higher.

A surface plot with the exactly same element net, but with material properties of the stress control mastic, stress control tube and the anti-tracking tube changed to air can be used to study the difference between a termination with stress control components and a bare termination without any sort of grading.

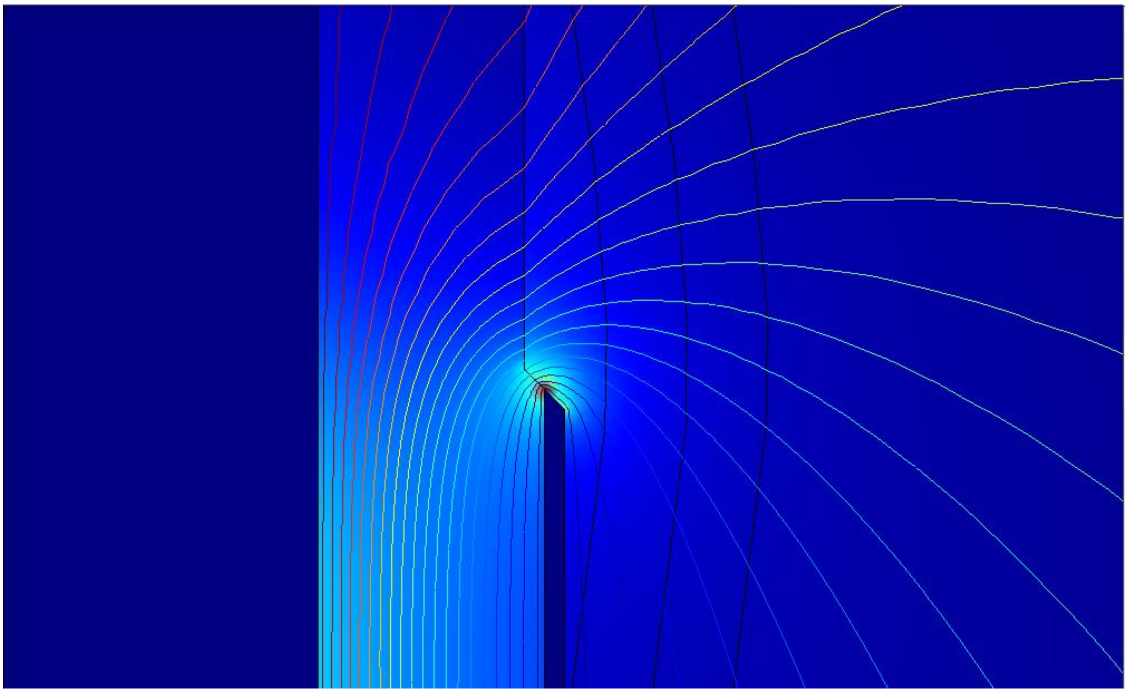


Figure 21. Electric field and equipotential lines in termination without grading

The electric field peak at the cutting point of the cable screening is much higher when no grading is used. The diverging of the electrodes causes the field to rise remarkably at the end of the grounded cable screening. The denseness of the equipotential lines at the cutting point clearly indicates a much higher electric field peak.

The magnitudes of the electric field peaks at the cutting point of the screening can be examined in figures 22 and 23. Figure 22 illustrate the electric field of a HITW1.24 termination and figure 23 a bare termination without any mass or tubes.

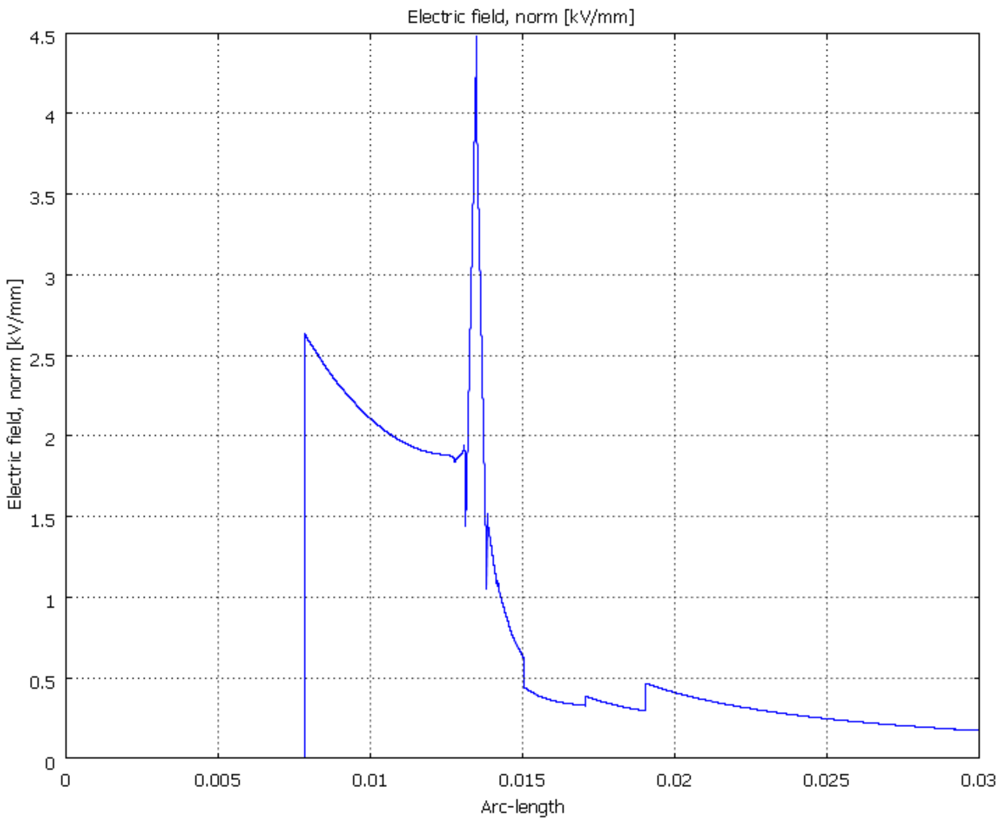


Figure 22. Magnitude of electric field in HITW1.24 termination

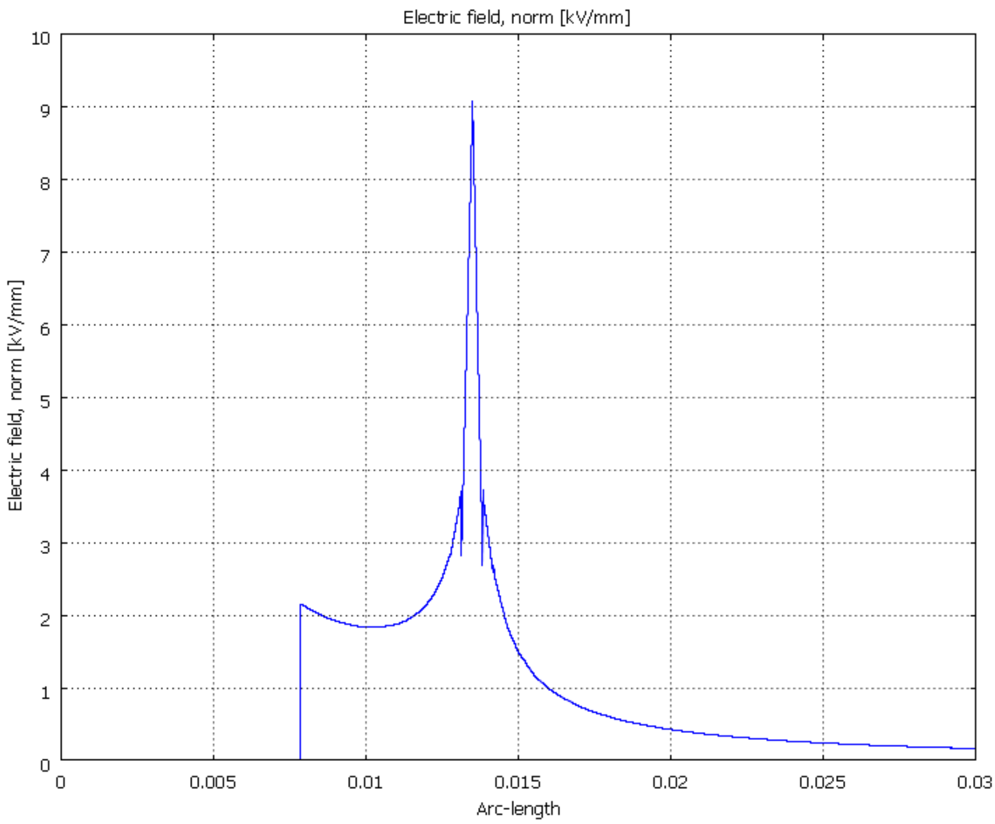


Figure 23. Magnitude of electric field in termination without grading

The graphs are drawn from line plots that start from the center of the conductor and go straight along the X-axis through the end of the cutting point and continue outwards. The length of the line is 30 mm and the resolution for the graph is 20000 points along the line. The unit of the line plot graph is by default V/m but kV/mm is more convenient when studying the dielectric strength of insulating structures.

The use of a HITW1.24 termination instead of a bare termination decreases the electric field peak at the cutting point of the screening roughly by 50 %.

6.3 Simulation of a MV cable joint

A medium voltage underground joint differs greatly from a termination in terms of electric field behavior. The joint is designed to imitate the shape of a cable and the diversion of electrodes is kept as small as possible.

Electric field peaks are generated at the surface of the connector as a result of sharp corners. Field peaks are also generated at the cutting points of both cable screenings but they are not as crucial as in a termination if no air bubbles are left inside the insulating structures.

The structure of a joint at the connector can be examined in figure 24.The shining layers on the left are the conductor and the connector. The insulation can be seen above the conductor in the lower part of the picture. On top of the connector is a layer of yellow stress control mass. The layer is hard to see since it was damaged while cutting the joint in half. The black layer on top of the mass is the stress control layer from the stress control tube. The red layers above it are the insulating layers from both the stress control tube and the insulating and semi-conductive tube. The black semi conducting layer can be seen above the red layers. On top of the semi-conducting layer are the copper gauze and finally the black sealing tube.

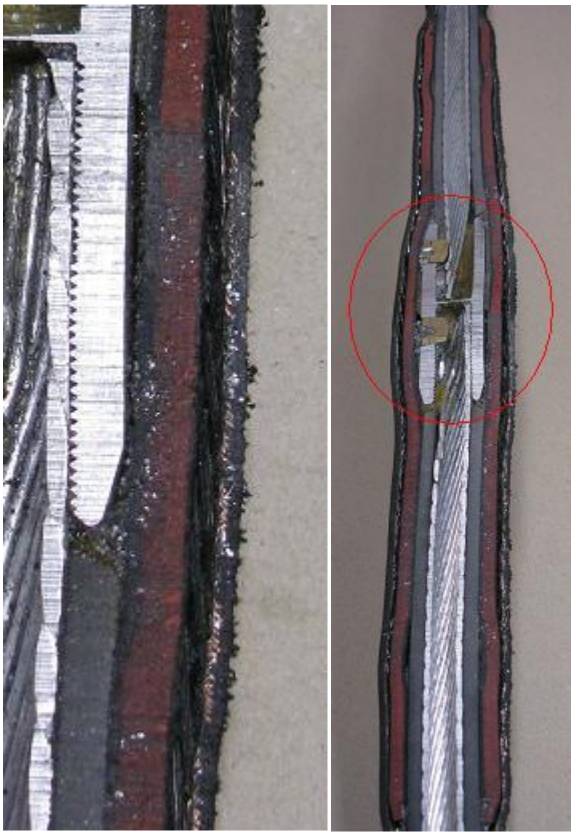


Figure 24. Connector in a HJW11.24 joint

The material properties used in the simulation are according to the values in table 1 and table 3. The electric potential in the conductor is set as 12 kV. The model used in the simulations consists of thin layers that caused problems with meshing. The mesh was created using free mesh parameters since default settings did not work in this model. The electric field and potential is displayed in the same way as in the termination. The field is displayed on the surface in a color scale and equipotential lines are represented as contours. The electric field peak at the cutting point of the cable screening is not examined since the behavior is almost the same as in a termination. The peak at the cutting point is much lower in a joint since the grounding electrode continues on top of the stress control and insulating tubes. However the stress caused in the insulating structures above the connector is relatively higher than in other parts of the joint. Peaks in electric field at this point of the joint can easily lead to failure.

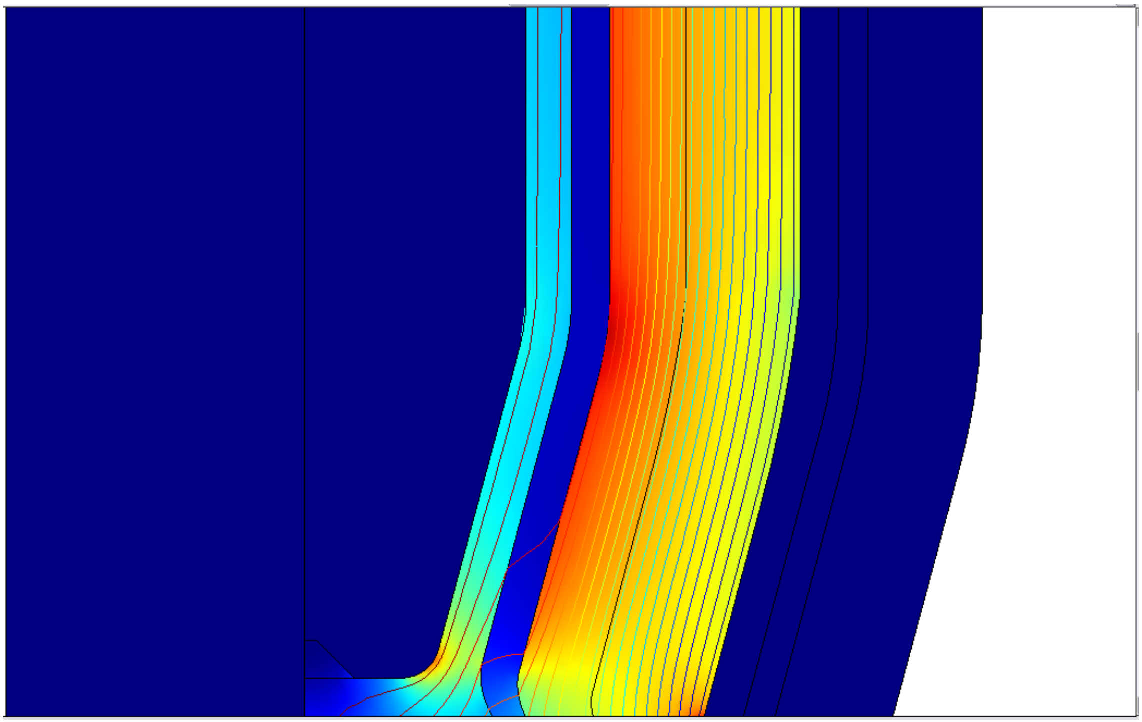


Figure 25. Electric field and equipotential lines in a HJW11.24 joint

The surface plot illustrates how the electric field is mainly divided within the insulating layers of both tubes. The field is also relatively high within the stress control mass and a peak can clearly be seen at the end of the connector. The highest peak in electric field is generated within the insulation as a result of the sharp shape used at the cone edge of the connector.

The magnitude of the electric field within the insulating structures of a HJW11.24 joint can be examined in figure 26. The graph is drawn from a line plot according to the red line in figure 27. The line starts inside the connector and goes through the cone edge in the connector body and through the point of the insulation with the highest peak in electric field.

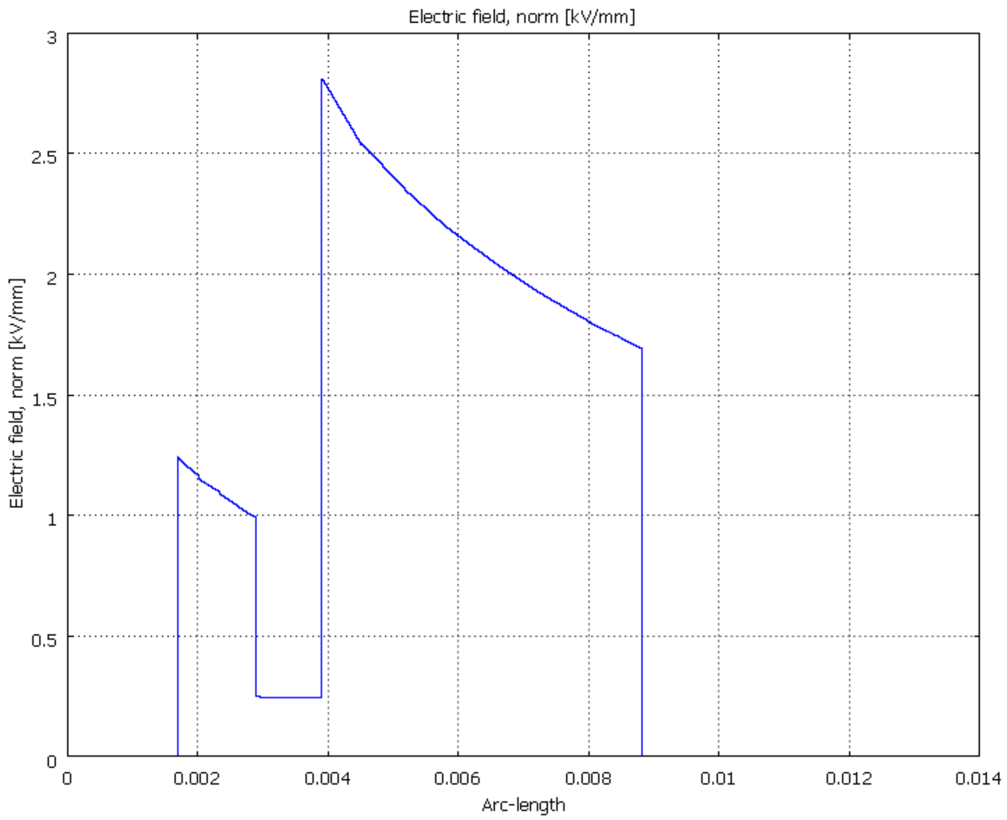


Figure 26. Electric field in HJW11.2403C joint

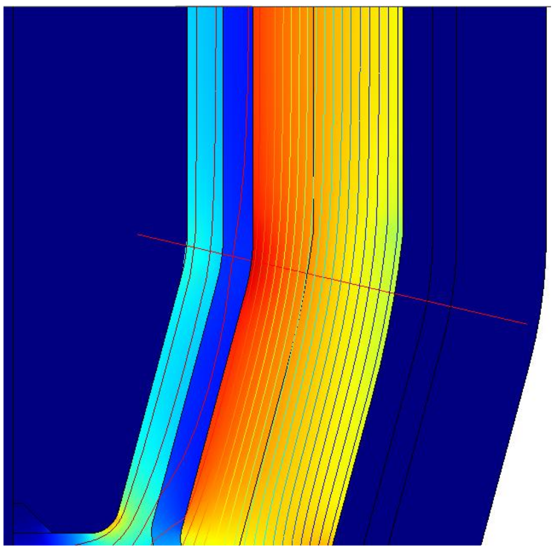


Figure 27. Model of line plot used in joint simulations

The length of the line is 14 mm and the resolution for the graph is 20000 points along the line. The unit of the line plot graph for the joint is also set as kV/mm.

7 VERIFICATION OF SIMULATION RESULTS

Measuring the electric field can be extremely hard since the probe used for measurement can disturb the field. The verification of simulation results was decided to be done by studying the behavior of terminations and joints in high voltage tests. The tests were performed using a Baur PGK 110 / 5 HB high voltage test set. Basic principle of the test setup can be seen in figure 27. The conductor was connected to the AC-output and the aluminum shield to ground.

Termination results were verified by performing a high voltage test where the voltage was raised with 4 kV steps up to 60 kV AC. The voltage was kept at each level for 1 minute before raising it to the next one. The voltage was kept at 60 kV for 15 minutes and then dropped down to 48 kV where it was kept for 4 hours. The voltage was finally raised back to 60 kV where it was kept for at least 30 minutes before ending the test.

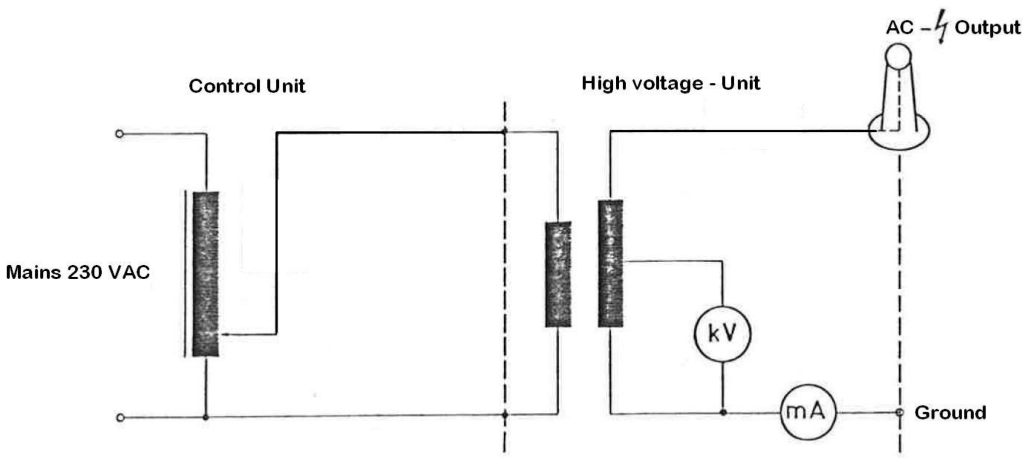


Figure 28. Principal high voltage test scheme

Twelve AHXAMK-W terminations were tested in order to verify the electric field defined in the simulations. Six of the terminations were tested without any stress control components and six with a HITW1.24 termination. Two terminations were tested simultaneously on one piece of cable. The bare terminations were tested first and the same cables were then used for testing the HITW1.24 terminations. The length between the cutting point of the screening and the connector lug was increased in the bare terminations to prevent flashovers from occurring.

Figure 29. Test setup for high voltage test

The behavior of all bare terminations was similar. Surface discharges could be heard clearly after the 40 kV. Visible slider discharges started to occur at the first 60 kV stage and the voltage could not be increased higher than this. The surface discharges continued to occur randomly after dropping the voltage to 48 kV. Loud slider discharges and flashovers started to occur between the connector lug and the cables screening after raising the voltage again to 60 kV. Regardless of the discharges none of the samples failed during the voltage test. Closer examining of the cutting point of the screening showed that the constant discharges and flashovers at higher voltages had burnt the insulation a bit. A termination of this type would eventually fail when the insulation would be damaged enough at the cutting point of the screening.

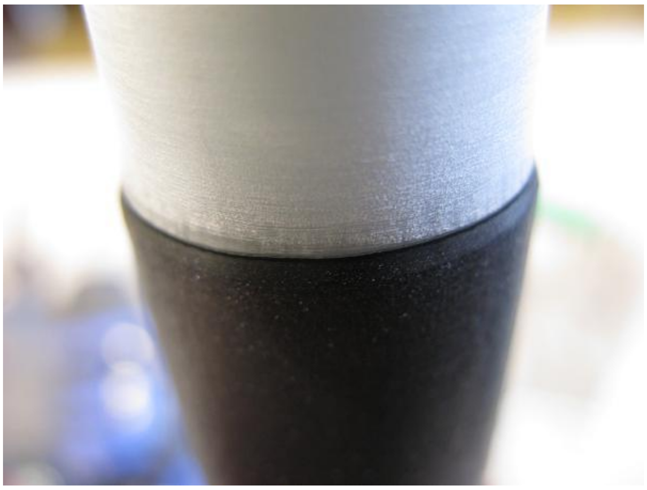


Figure 30. Burning marks at cutting point of screening

Both ends of the cables were cut off before installing the HITW1.24 terminations. The terminations were installed according to the installation instructions. There was no surface discharges or flashovers noticed during the test. One of the HITW1.24 did however fail after 12 minutes at the first 60 kV stage. The broken termination was cut off and a new termination was installed on the cable. The new sample passed the whole test without any problems.

The broken termination was cut open to study the reason for the failure. A breakthrough had occurred at the cutting point of the screening which caused the insulation to melt and allowed current to flow between the conductor and the grounded cable screening. The hole in the insulation was not exactly at the cutting point but instead a bit away from it. This had probably been the weakest point in the insulation. The reason for the failure is unknown since no clear installation error could be noticed. Installation errors are a common reason for failures of this type. The breakthrough could also be a result of quality issues in the stress control mass or even in the cable insulation. Wrong electric properties in the mass could lead to a much higher electric field at the cutting point of the screening. Improper structure of the mass could also lead to a breakthrough if air bubbles were left inside the termination. Partial discharges generated inside the air bubbles would start to slowly burn the insulation and could lead to failure.

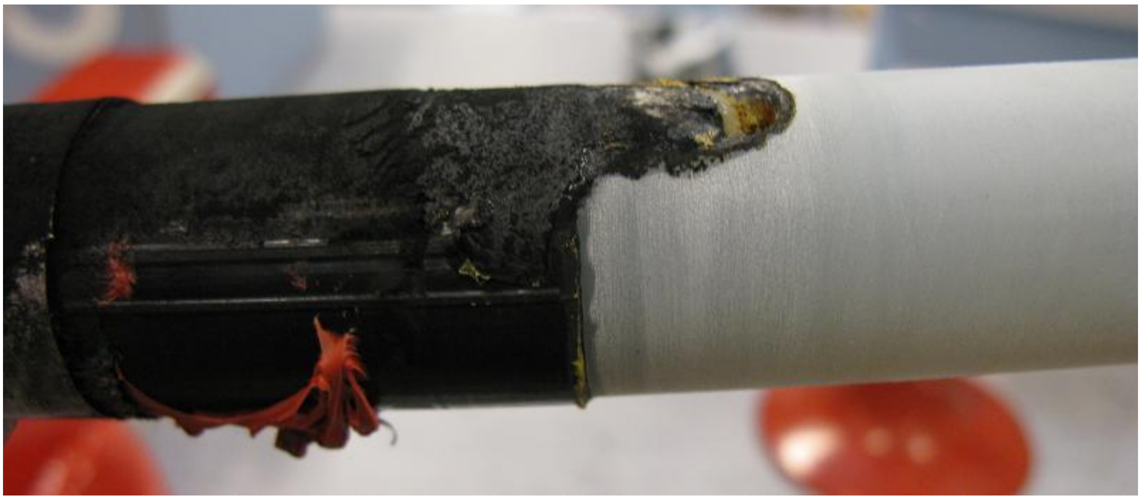


Figure 31. Breakthrough in HITW1.24 termination

The testing of joints was too time-consuming so the verification of electric field behavior was done by studying old test reports. A suitable test report was found where partial discharge measurements were performed for eight single core AHXCMK-WTC terminations and joints. A high voltage test was performed for six of the cable assemblies after the PD-measurements. The voltage was first raised to 40 kV AC and kept there for 4 hours. The voltage was then raised to 80 kV. The test was ended if no breakthrough occurred at 80 kV. (Laboratory report no.:1850S)

Four of the tested cable assemblies failed during the test. The failure was caused by a breakthrough at the connector of the joint in all four cable assemblies. Three of the breakthroughs occurred at the cone edge of the connector and one of the assemblies failed at a sharp corner of a shear head bolt. (Laboratory report no.:1850S)

The reason for the breakthrough at the shear head bolt was caused by an installation error. A sharp corner of the bolt was not properly rounded before applying the stress control mass. This kind of failures could be avoided by adding a semiconducting layer on top of the connector body to smoothen electric field peaks at sharp edges. The breakthrough at the cone edge of the connector is however a result of the stress caused at the edge. Improper material properties in the stress control mass gives rise for a higher electric field within the mass. Air bubbles left inside the mass would lead to partial discharges which eventually cause a breakthrough inside the joint.

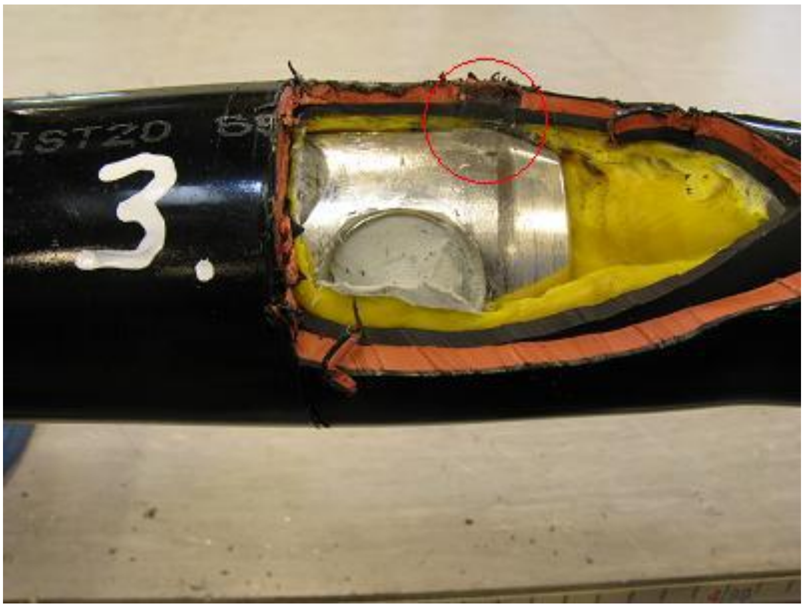


Figure 32. Example of failure at cone edge of connector (Laboratory report no.:1850S)

The high voltage test results clearly show that the cutting point of the cable screening is the weak point in a termination. All terminations without grading suffered from the high electric field peak and would eventually have failed with such a high voltage. The HITW1.24 terminations that passed the test showed no sort of signs of a high electric peak at the cutting point of the screening. It can thereby be assumed that the grading at the cutting point of the screening actually works and the electric field peak is decreased significantly. The failure of a HITW1.24 termination however indicates how important it is to have correct material properties and to avoid installation errors. Issues like these can easily make the situation even worse than it is in a termination without any sort of grading.

The test report indicates that the weakest point of a cable joint is the cone edge of the connector. The material properties of the stress control mass play a key role in the durability of a cable joint of this type.

The high voltage results and the test report both support the electric field behavior of the simulations. The simulation software can thereby be used as an indicative tool to improve the electric field in medium voltage accessories.

8 PRODUCT OPTIMIZATION

The product optimization was done by modifying material properties in the models. No changes were made to the original structure of the termination and joint. The properties for insulating materials are generally quite equal but a wide variety of different stress control components are available. Because of this the optimization was done by studying how different stress control materials affect the electric field behavior. The aim was to find out an optimal solution for the current structure of terminations and joints.

Different manufacturers offer a variety of stress control masses with relative permittivities between approximately 10 and 20. The conductivities of the masses are generally between 1e-8 and 1e-12. The properties of tubes also vary greatly as relative permittivities go from about 20 to 40 and conductivity from 1e-7 to 1e-13.

The affect of permittivity and conductivity were studied separately. The lowest and highest possible permittivity was simulated with a fixed conductivity value. The lowest and highest possible conductivity was then simulated with a fixed permittivity value. The fixed value was chosen so that it was in the middle of the lowest and highest value.
This kind of an approach offers eight different solutions for the termination and the joint and gives a good idea of an optimal solution. The material properties used in each simulation setup can be seen in table 4.

Table 4. Simulation setups

	Stress control mass		Stress control tube	
Simulation setup	**Permittivity [ε_r]**	**Conductivity [σ]**	**Permittivity [ε_r]**	**Conductivity [σ]**
1	10	1.00E-10	20	1.00E-10
2	10	1.00E-10	40	1.00E-10
3	20	1.00E-10	20	1.00E-10
4	20	1.00E-10	40	1.00E-10
5	15	1.00E-08	30	1.00E-07
6	15	1.00E-08	30	1.00E-13
7	15	1.00E-12	30	1.00E-07
8	15	1.00E-12	30	1.00E-13

The material properties for the cable insulation and screening are according to table 1 in all simulations setups. The material properties for all insulating layers and the semi-conductive layer in the joint are according to table 5 in all simulation setups.

Table 5. Electric properties of insulating and semi-conductive layers used in simulations

Material	Conductivity [σ]	Permittivity [εr]
Insulating layers	1.00E-11	3.5
Semi-conducting layer	1.00E-03	1

All simulations were done using the same boundary and mesh setting as described in chapter 6. The setting for the line plot used for measuring the electric field was also the same as in chapter 6. The simulation results for the termination can be seen in table 6. The "Field peak" in the table indicates the peak value at the cutting point of the screening between the cable insulation and stress control mass.

The results indicate that using a higher permittivity for both the mass and the tube is better. For conductivity the situation is similar, higher conductivity leads to a lower electric field peak. It is clearly seen from the simulation results that the permittivity affects the result more than conductivity does. The permittivity of the mass has a higher impact on the resulting peak. The highest permittivity for the mass and the tube in setup 3 results in about 25 % lower electric field peak at the cutting point of the screening than it would be with the lowest permittivity values in setup 1.

The conductivity of materials does not affect the electric field peak greatly. The highest conductivity for the mass and tube in setup 5 only results in about 3 % lower electric field peak at the cutting point of the screening than it would be with the lowest conductivity values in setup 8.

Table 6. Field peak results for terminations

Simulation setup	**Field peak [kV/mm]**		**Simulation setup**	**Field peak [kV/mm]**
1	5.45		**5**	4.5
2	5.3		**6**	4.6
3	4.15		**7**	4.55
4	4.05		**8**	4.65

Combining the permittivities from setup 4 and the conductivities from setup 5 results in an electric field peak of 4 kV/mm. The combination of permittivities from setup 1 and conductivities from setup 8 results in an electric field peak of 5.5 kV/mm. When no grading at all is used the resulting electric field peak is approximately 9 kV/mm.

The difference between the best and the worst setup is significant. The use of the highest permittivities and conductivities leads to about 55 % lower electric field peak than without any grading. The lowest permittivities and conductivities lead to about 39 % lower electric field peak than without any grading.

The structure of the joint results in a bit more complicated field than in that of a termination. The resulting line graph shows two peaks in the electric field at the cone edge of the connector. The first peak is at the surface between the connector and the stress control mass and the second is at the surface between the stress control tube and the insulating layers. The second peak between the stress control layer and the insulating layer is much higher than the one at the connector surface. This peak is generated between two layers of a two layer tube and the bond can be assumed to be of extremely good quality. Because of this we can assume that this is not the most critical point. The peak at the connector surface seems to be more important regarding the durability of a joint.

The simulation results for the joint can be seen in table 7. The first value in "Field peak" column is the peak at the surface of the connector and the second is the peak inside the stress control tube. The results for the joint also indicate that permittivity affects the resulting electric field more than conductivity does. The best combination is however not with the highest possible permittivity for the mass and the tube in setup 4. A high permittivity mass and a low permittivity tube in setup 3 results in a slightly lower peak at the surface of the connector.

The changes in conductivity are almost insignificant to the resulting electric field. A high conductivity mass and a low conductivity tube in setup 6 seem to be slightly better than other combinations.

Table 7. Field peak results for joints

Simulation setup	**Field peak [kV/mm]**		**Simulation setup**	**Field peak [kV/mm]**
1	1.25 / 2.7		**5**	0.8 / 2.95
2	1.3 / 2.8		**6**	0.8 / 2.85
3	0.65 / 2.85		**7**	0.85 / 2.95
4	0.7 / 2.95		**8**	0.85 / 2.85

The use of a high permittivity mass leads to roughly about 50 % lower electric field peak at the surface of the connector than with low permittivity. The permittivity of the tube does not affect the electric field at the surface of the connector by much in a cable joint of this type. The use of a stress control tube at this point of the joint seems pointless and is more likely used for ease of installation.

The performance of a joint could be improved by adding a semi-conducting layer on top of the connector before applying the stress control mass. The semi-conducting layer would smooth the surface and therefore prevent electric field peaks from being generated. The use of a semi-conducting mass or tube could possibly replace the stress control mass completely above the conductor.

9 CONCLUSION

The aim for the thesis was to study how relative permittivity and volume resistivity of stress control components affected the electric field in a medium voltage underground termination and joint.

Material properties of the stress control components play a key role in the durability of a termination or a joint. The results indicate that permittivity has a much higher effect on the resulting electric field than volume resistivity has. It should be noted that the permittivity is not a constant in reality, as it was assumed in the simulations.

The electric field peaks are relatively low with the 12 kV voltages that were used in the simulations. It is however important to note that all simulations represent ideal insulators without any air bubbles or dirt between layers. In reality no insulator is ideal and microscopic air bubbles exists in all layers. Therefore the resulting electric field is always higher than that represented in simulations.

The literature study and the simulations revealed that the current structure of the joint could be improved. Adding a semi-conductive layer on top of the connector would decrease the faults caused by installation errors but the ease of installation would possibly suffer.

The simulation of electric field offers great potential when comparing material properties of insulating structures. Structural changes could also be examined but it in this case it is important to have a small enough element net to get reliable results. Adding more physical conditions like heating to simulations could be a subject for future research. The stress control materials always have some sort of loss factor that affects the performance of these materials.

Only basic functions of COMSOL Multiphysics were used in this thesis. The software offers a lot of functions and specified options that were not used at all. The version of COMSOL Multiphysics that was used is 3.5a. A newer 4.0 version was released during the making of this thesis. The newer version offers more functions and new physical modeling environments. The support for different file types is also improved in the new version.

The 3D file suitability with pro/engineer files was disappointing at first. The expectation was to use relatively big 3D models of the complete products in simulations. There were also problems with the 2D file conversions in the beginning. These problems were solved once the correct settings were found. The issues with the 3D models were never completely solved but smaller parts of the models could be simulated with the help of COMSOL's personnel. The source for the problems was related to the complexness of the models and errors that occurred in the conversion between different file formats.

Regardless of the issues, my general opinion of COMSOL Multiphysics is positive. The approach to use 3D models in the thesis was not the best possible and it is something I would not do again if I should start with a similar project. The software is easy to use and offers a lot of functions and usability for product development purposes.

Besides product development software like COMSOL Multiphysics offer great utilization for other purposes. Elegant visual field plots could for example be used in training and sales to gives a better picture of the company for outside persons.

REFERENCES

Aarnio, Anssi. 2010, *Characterization of non-metallic materials for medium voltage cable accessories*, Master's thesis, Tampere: University of Technology, Material Science.

AC/DC Module. COMSOL Multiphysics. [Cited: 15.8.2010] Available at: http://www.comsol.fi/products/acdc/

Aro, Martti; Elovaara, Jarmo; Karttunen, Matti; Nousiainen, Kirsi & Palva, Veikko. 2003, *Suurjännitetekniikka*, 2nd ed., Otatieto, 520 p.

Borstar® HE6062 datasheet, 9.7.2010, 2nd ed., Borealis. [Cited: 28.10.2010] Available at: http://www.borealisgroup.com/datasheets/10025446

CAD Import Module. COMSOL Multiphysics. [Cited: 15.8.2010] Available at: http://www.comsol.fi/products/cad-import/

COMSOL Multiphysics. [Cited 15.8.2010] Available at: http://www.comsol.fi/products/multiphysics/

Electrical conductivity, Wikipedia. [Cited: 28.10.2010] Available at: http://en.wikipedia.org/wiki/Electrical_conductivity

Elovaara, Jarmo & Laiho, Yrjö. 1988, *Sähkölaitostekniikan perusteet*, 2nd ed., Otakustantamo, 487 p.

Hirvonen, Markus. 2008, *Effect of assembly error on partial discharge levels in medium voltage terminations*, Engineering thesis, Helsinki: Stadia, Power Systems.

HITW1.2403L product card. Ensto Finland Oy. [Cited: 16.9.2010] Available at: http://products.ensto.com/catalog/11051/product/15771/HITW1.2403L_ENG1.html

HJW11.2403C product card. Ensto Finland Oy.. [Cited: 16.9.2010] Available at: http://products.ensto.com/catalog/11041/product/15853/HJW11.2403C_ENG1.html

Laboratory report no.:1850S, 9.4.2010, Ensto UN Laboratory.

LE4201R datasheet, Borealis. [Cited: 16.9.2010] Available at: http://www.borealisgroup.com/datasheets/10024590

Obituary: Germund Dahlquist. 1.5.2005, Society for Industrial and Applied Mathematics. [Cited: 15.8.2010] Available at: http://www.siam.org/news/news.php?id=54

Reka kaapeli OY. DRYREX Korkealaatuiset keskijännitekaapelit. [Cited: 16.9.2010] Available at: http://www.reka.fi/files/965_Korkealaatuisetkeskijnnitekaapelit.pdf

Training Module: Ensto Underground Solutions, Ensto Utility Networks. [Cited: 28.10.2010].

Visico™ LE0540 datasheet, 19.11.2009, 15th ed., Borealis. [Cited: 28.10.2010] Available at: http://www.borealisgroup.com/datasheets/10011400

Wolfson, Richard. 2007, *Essential university physics*, Pearson Education Inc., 728 p.

APPENDICES

1. HITW1.24 Installation instructions
2. HJW11.24 Installation instructions

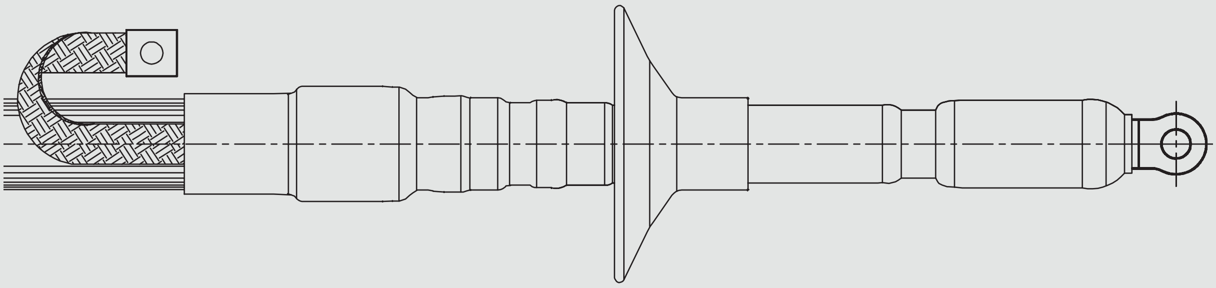
INSTALLATION INSTRUCTION

PEM1074ENG

2008-08

HEAT SHRINK INDOOR TERMINATIONS HITW1.24
HEAT SHRINK OUTDOOR TERMINATIONS HOTW1.24

ENGLISH



GENERAL INFORMATION

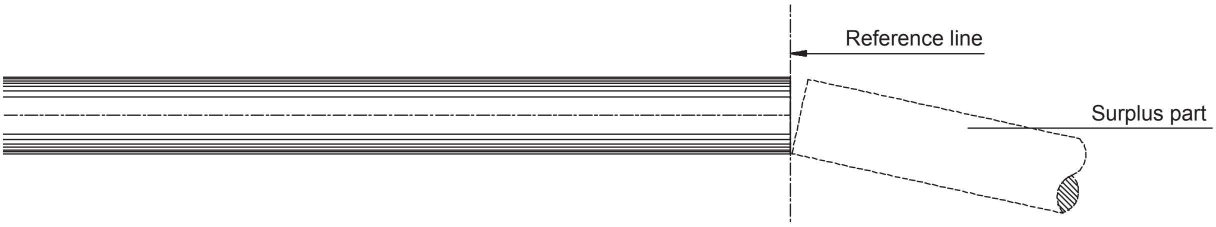
- Check that the kit is suitable for the cable type.
- Check the materials listed in the bill of materials for completeness.
- Read the installation instructions carefully before starting the installation.
- Install carefully and make sure the materials are clean during the installation.
- Clean the working place after the installation.

GENERAL INSTRUCTONS FOR HEAT SHRINKING

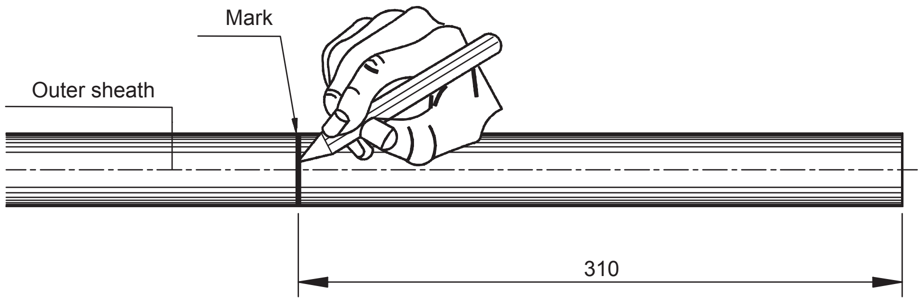
- Please note that in some working places a hot work licence is needed.
- Use a propane burner with a flame length of approx. 20-30 cm. Do not use too large or sharp flame.
- Move the flame all around the cable on the shrinking direction. Move the flame continuously to avoid overheating.
- Make sure that the ventilation is good and there are no flammable materials around.
- Clean the cable surfaces before shrinking.
- When shrinking, always follow the installation instructions and the relevant sequence to avoid trapped air.
- Check that the tube has shrunk evenly around the cable before you continue shrinking.
- If the tube turns around at the end of shrinking, straighten the tube by directing the flame inside the tube from the opposite direction.
- After shrinking the tubes should be smooth and even following the shape inside.

LEGAL NOTICE

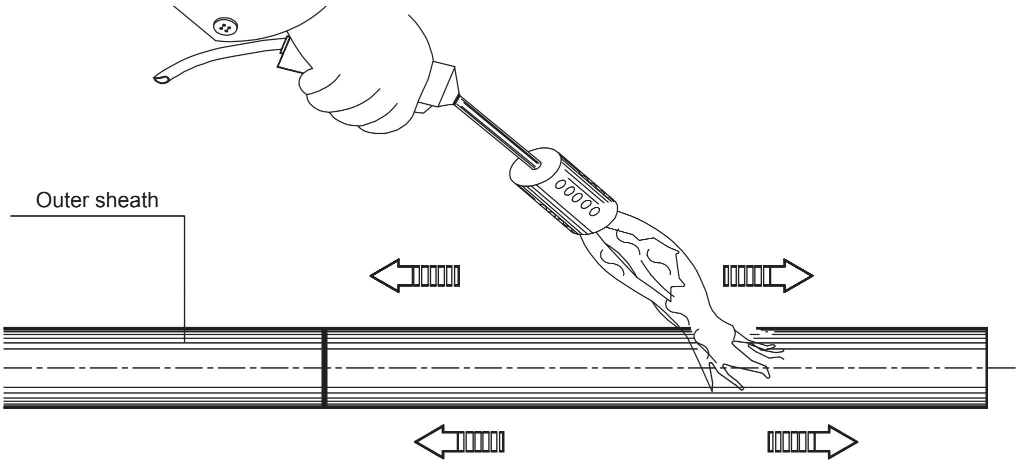
- The product must be installed only by a competent person with sufficient training in installation practices and with sufficient knowledge of good safety and installation practices in respect of electrical equipment. If local legislation contains provisions in respect of such training or sufficient knowledge in respect of installation of electrical equipment such provisions shall be fulfilled by the said person.
- Ensto accepts no liability concerning claims resulting from misuse, incorrect installation or ignored national safety regulations or other national provisions.
- WARNING: Failure to follow the installation instructions may result in damage to the product and serious or fatal injury.



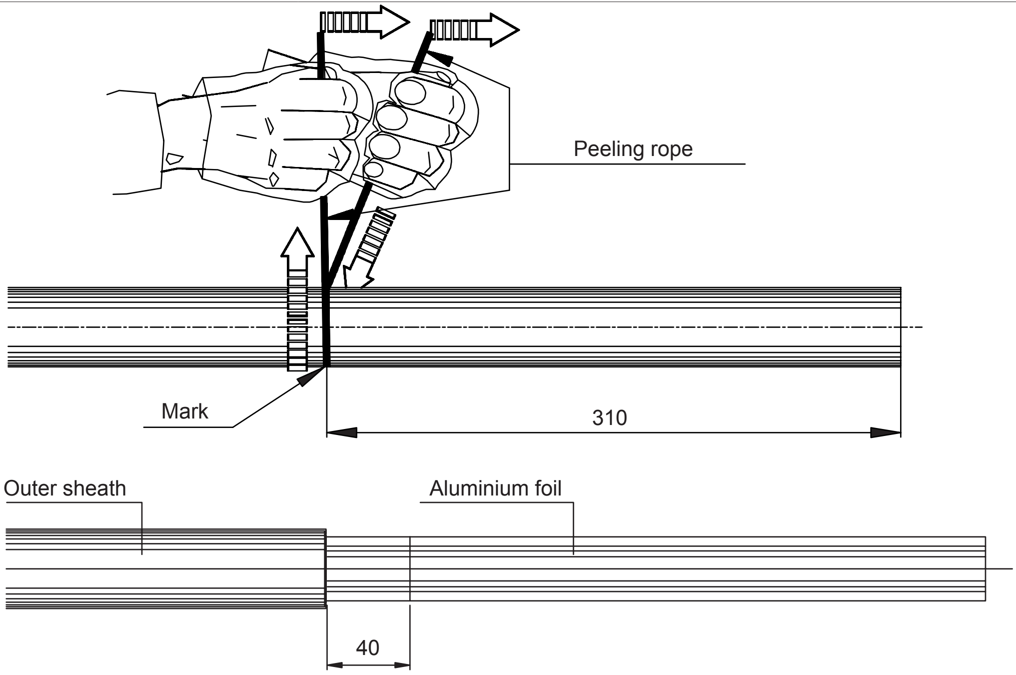
1. Check the length of each core according to the final installed position.



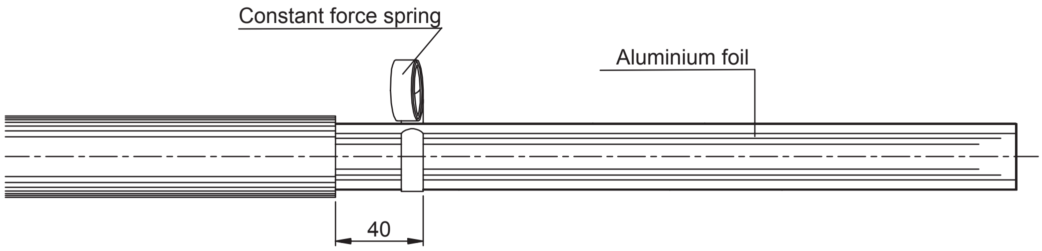
2. Mark the cutting point at the distance of 310 mm from the core end.



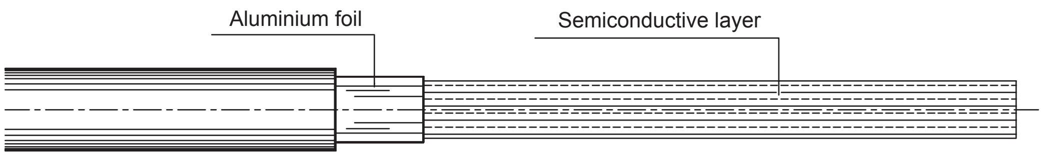
3. Heat the outer sheath up to the mark.



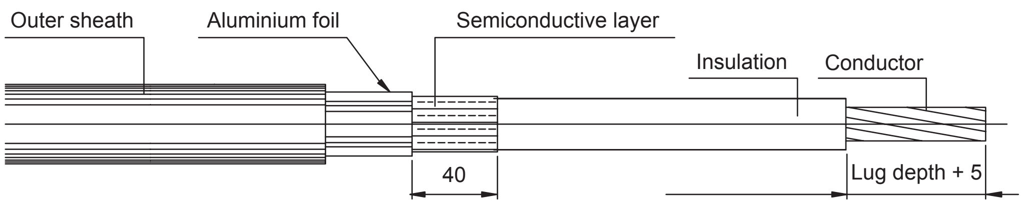
4. Use the peeling rope to remove the outer sheath to leave the aluminium foil exposed. Heat the aluminium foil close to the outer sheath with gentle flame. Remove the most of the adhesive coating from the aluminium tape for up to 40 mm from the outer sheath by the help of the peeling rope. Use the grinding paper included in the kit to remove rest of the adhesive coating from the aluminium foil up to 40 mm from the outer sheath. Take care that the aluminium tape does not break during the grinding.



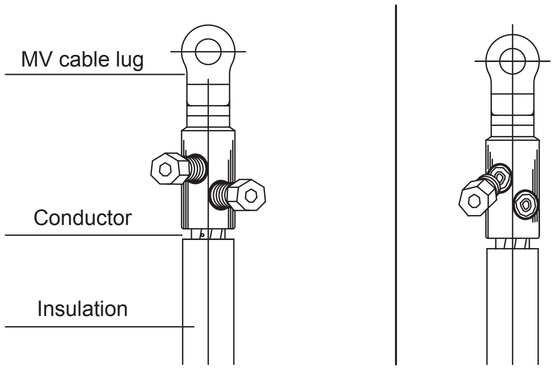
5. Install the constant force spring 40 mm away from the end of the outer sheath. Remove the aluminium foil by tearing it against the constant force spring.



6. Move the spring a little towards the core so that the aluminium foil edge remains under the spring. Tear the swelling tape in longitudal strips up to the spring. Remove the tape strips by tearing them against the spring. Remove the constant force spring.

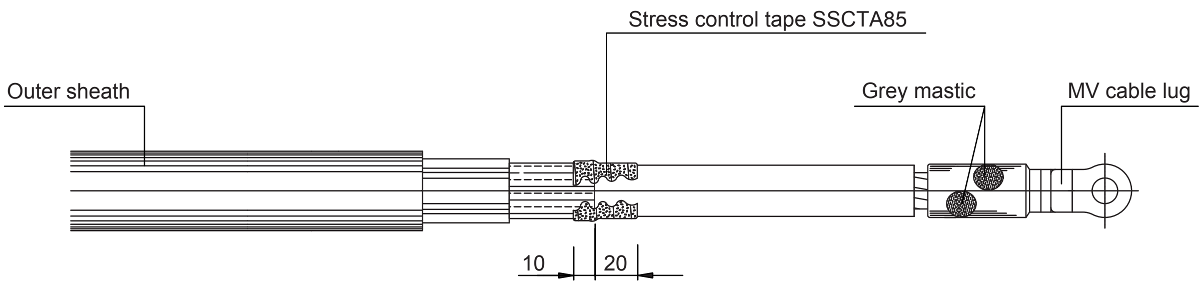


7. Remove the semiconductive layer leaving 40 mm measured from the Al foil. Use a suitable tool. If necessary, remove any remaining of the semiconductive layer with a piece of glass. Use the grinding paper included in the kit to smooth the insulation. Remove the insulation for the length equivalent to the bolt cable lug depth + 5 mm. If you use compression lugs, remove the insulation following the lug manufacturer's instructions. Be careful not to nick the conductor. Clean the conductor.

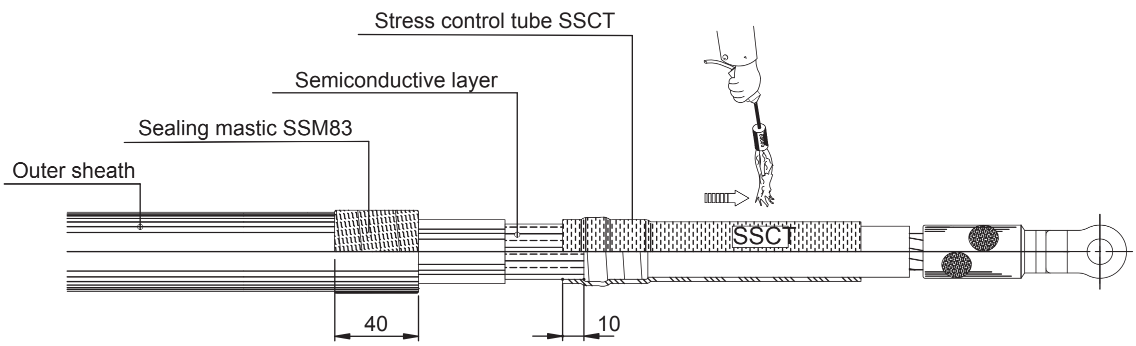


8. Install a suitable cable lug following the manufacturer's instructions. Remember to orient it correctly and to remove any sharp edges. Fill the holes with grey mastic.

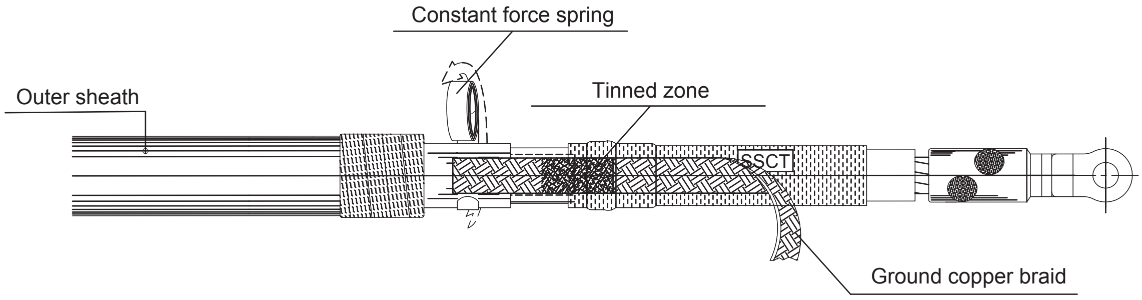
9. Clean the cable insulation with a cleaning tissue. Go towards the semiconductive layer, and finally clean the semiconductive layer without touching the insulation. Thus no semiconductive particles are deposited on the insulation.



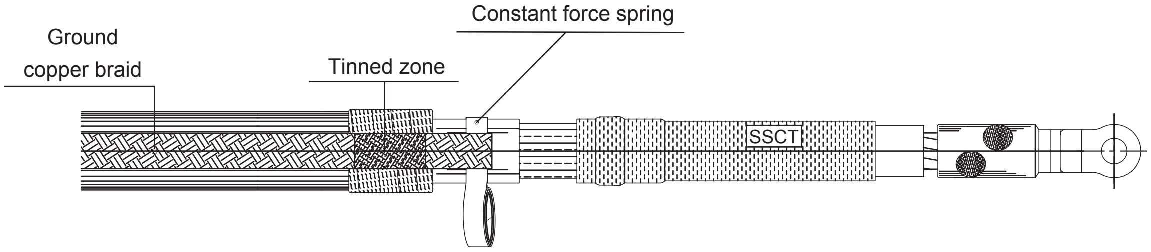
10. Wrap two layers of stress control tape SSCTA85 over the edge of the semiconductive layer. Wrap the tape for 10 mm on the semiconductive layer and 20 mm on the insulation. Start from the semiconductive layer. Stress control tape SSCTA85 must be wrapped with a 50 % overlap by stretching it to half of its original width.



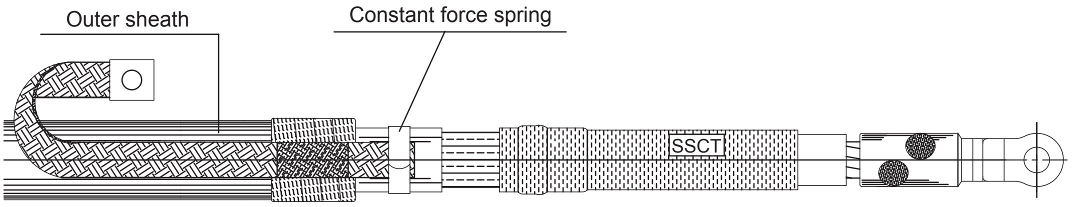
11. Place the stress control tube SSCT so that it overlaps 10 mm of the semiconductive layer. Start shrinking of the stress control tube from the end located on the semiconductive layer and continue towards the other end. Wrap one layer of sealing mastic SSM83 for 40 mm length on the outer sheath. Sealing mastic SSM83 must be wrapped by stretching it a bit.



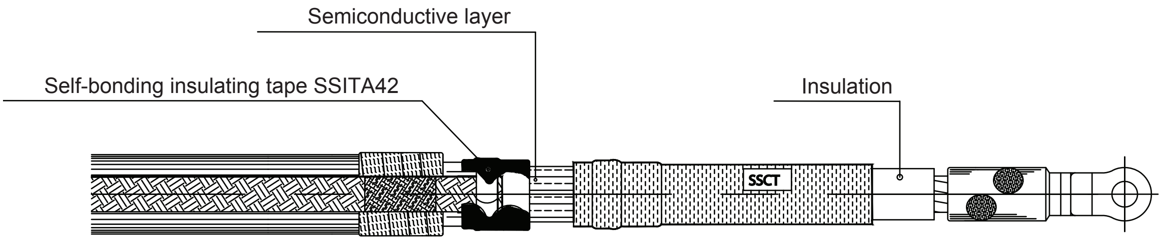
12. Place the end of the ground copper braid closest to the tinned zone (water block) on top of the exposed aluminium foil and fix the ground copper braid on the top of the aluminium foil with one turn of the constant force spring.



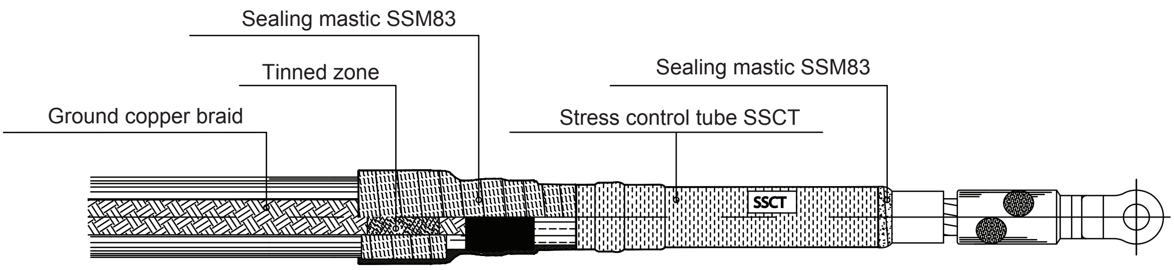
13. Fold the ground copper braid over the constant force spring so that the tinned zone remains on the sealing mastic.



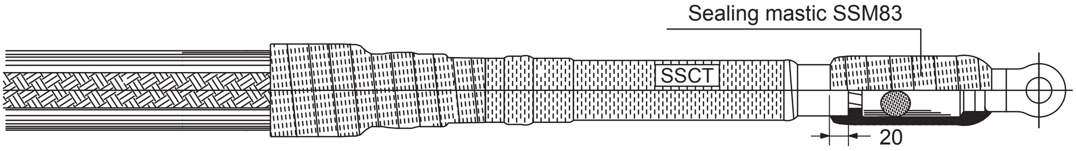
14. Wrap the rest of the constant force spring around the cable.



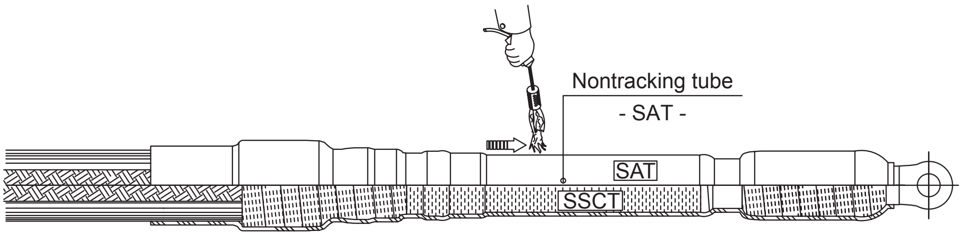
15. Wrap some layers of self-bonding insulating tape SSITA42 on the constant force spring and on the exposed aluminium foil to smooth the sharp edges. Self-bonding insulating tape must be wrapped by stretching it a bit. Wrap the tape to the direction, which tightens up the constant force spring.



16. Fill the gaps between the ground copper braid tinned zone and the outer sheath with some sealing mastic SSM83. Then wrap one layer of the same mastic to cover the ground copper braid tinned zone area and the constant force spring area up to the edge of the SSCT stress control tube. Sealing mastic SSM83 must be applied by stretching it a bit. Wrap one layer of sealing mastic SSM83 by stretching it a bit around the other end of the SSCT stress control tube to fill and smooth the transition between the tube and the insulation.

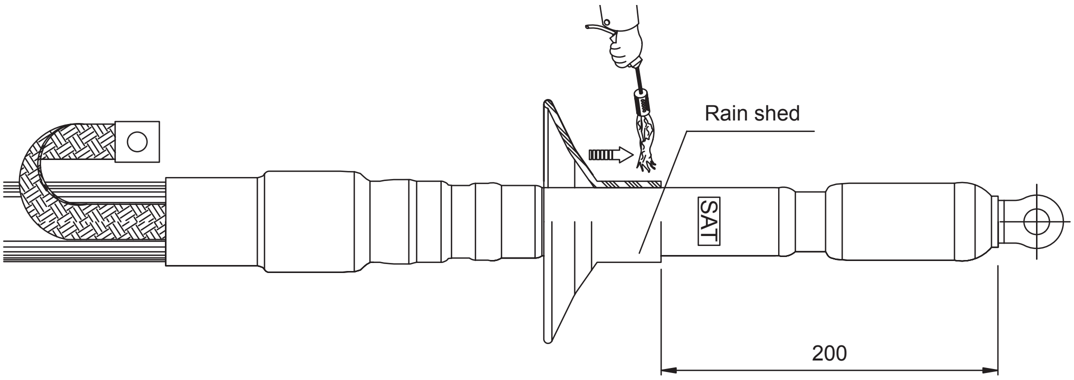


17. Fill the gap between the end of the cable lug and the insulation with sealing mastic SSM83. Then apply two layers of sealing mastic SSM83 to cover 20 mm of insulation and the barrel of the cable lug. The sealing mastic must be applied by stretching it a bit.

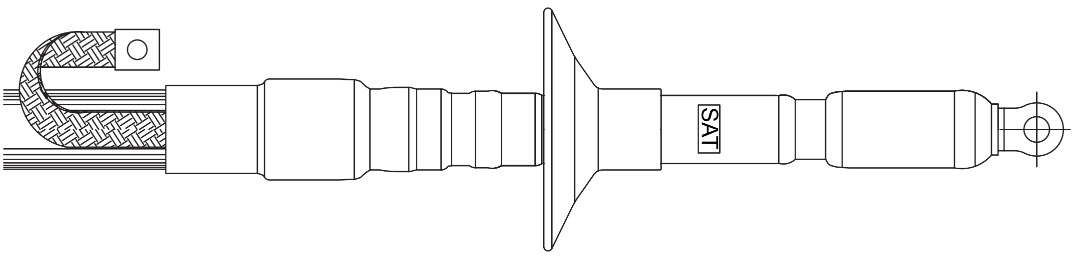


18. Place the SAT nontracking tube so that it covers the cable lug barrel completely. Shrink the tube starting from the cable sheath end.

24 kV INDOOR TERMINATION HITW1.24

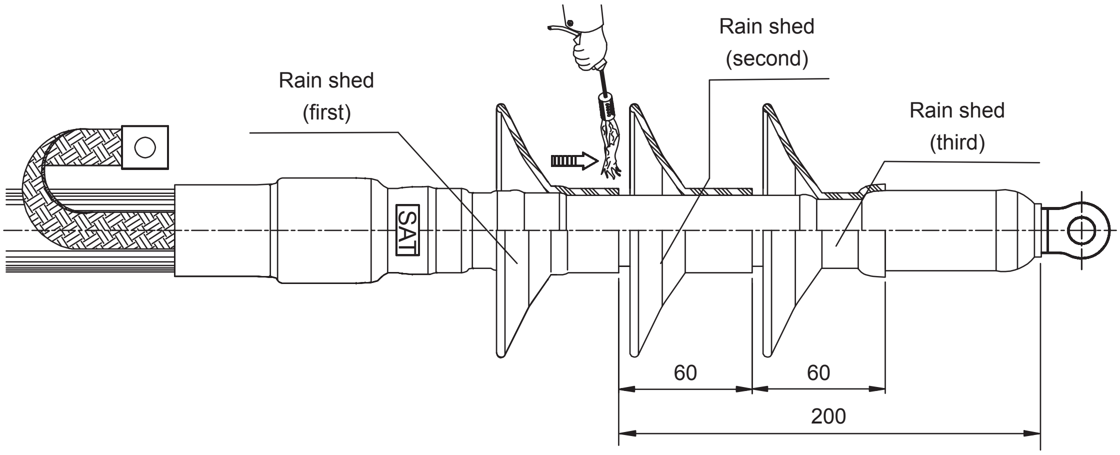


19. Place the rain shed so that the shed neck edge is at 200 mm from the the nontracking tube end. Shrink the rain shed directing the heat only to its neck.

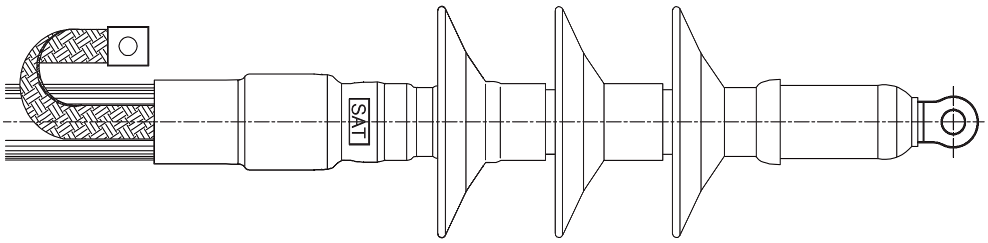


20. Indoor termination HITW1.24 is finished and ready to use!

24 kV OUTDOOR TERMINATION HOTW1.24

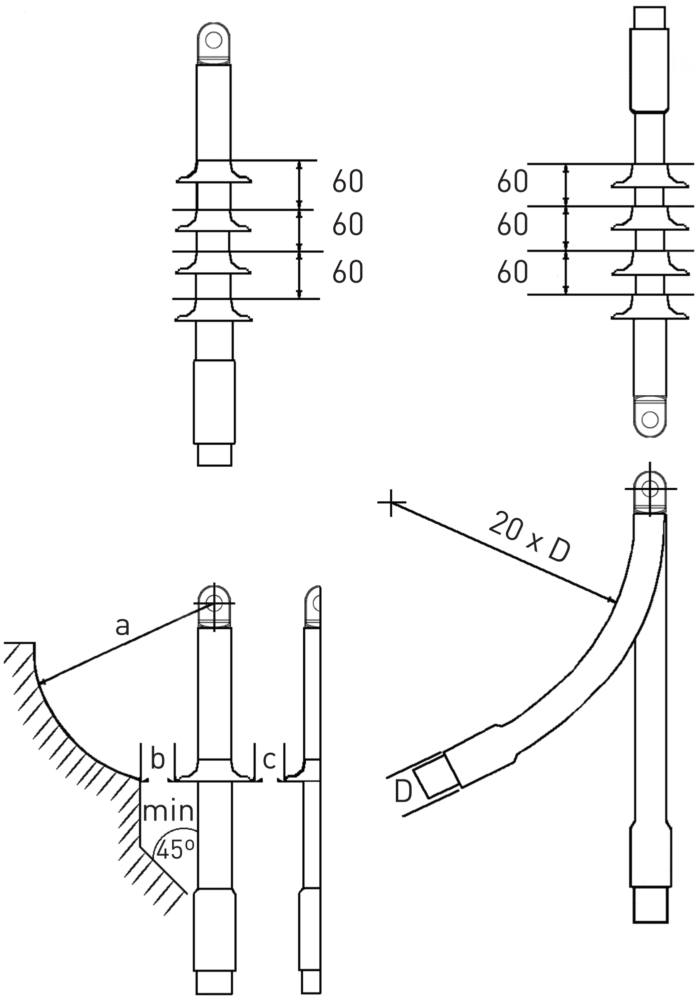


21. Place the rain shed so that the shed neck edge is at 200 mm from the nontracking tube end. Shrink the rain shed directing the heat only to its neck. Shrink the other two rain sheds so that they are spaced 60 mm.



22. Outdoor termination HOTW1.24 is finished and ready to use!

23. Install the LV cable lug included in the kit on the separate earthing conductor of the cable.



a = according to local requirements

Um kV	b min mm	c min mm
12	15	10
17,5	20	15
24	25	20
36	30	25

PEM1074ENG / Issue 2008-08-29

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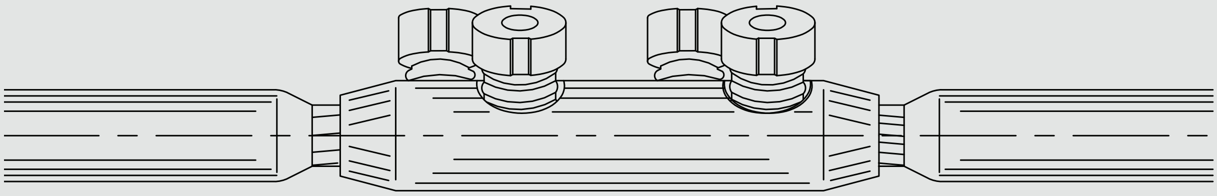
INSTALLATION INSTRUCTION

PEM1068ENG

2009-12

HEAT SHRINK JOINTS HJW11.24

ENGLISH



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- Clean the working place after the installation.

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- Make sure that the ventilation is good and there are no flammable materials around.
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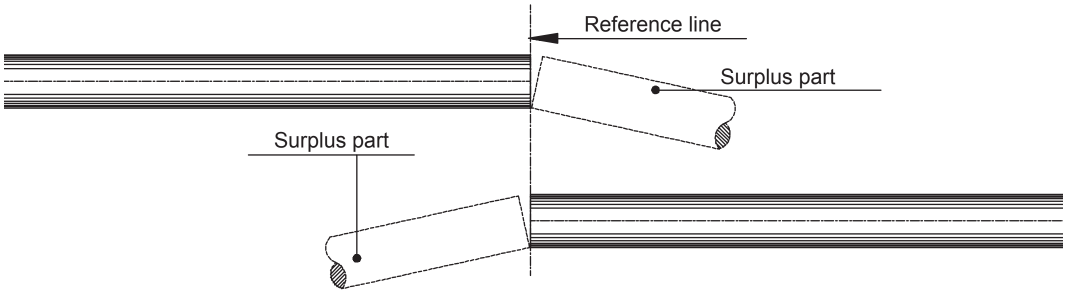
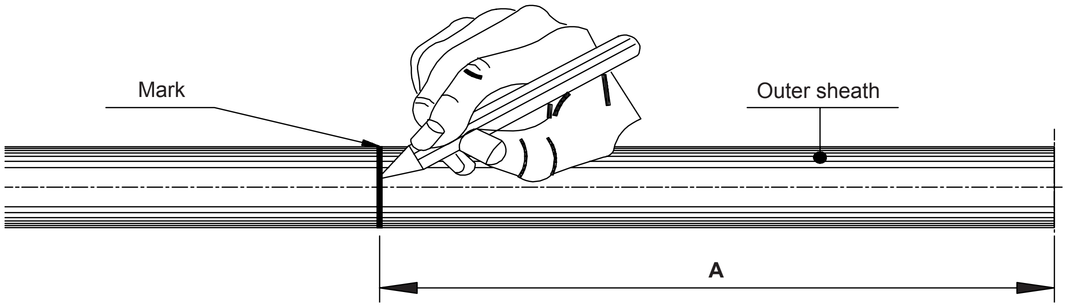
- WARNING: Failure to follow the installation instructions may result in damage to the product and serious or fatal injury.



1. Check the length of each core according to the final installed position.

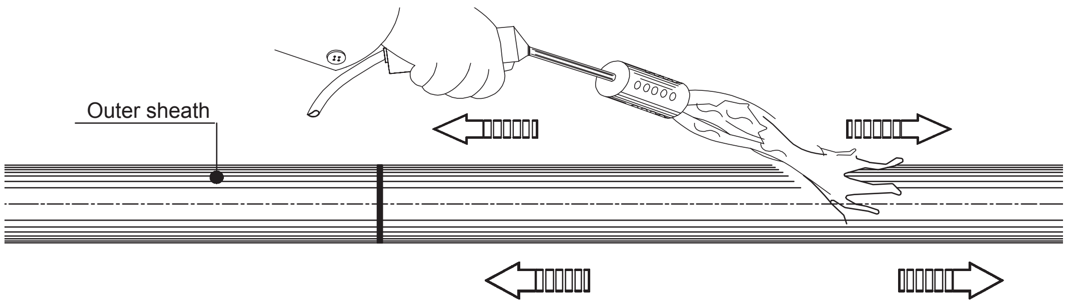


2. Mark the cutting point at the distance A from the core end.

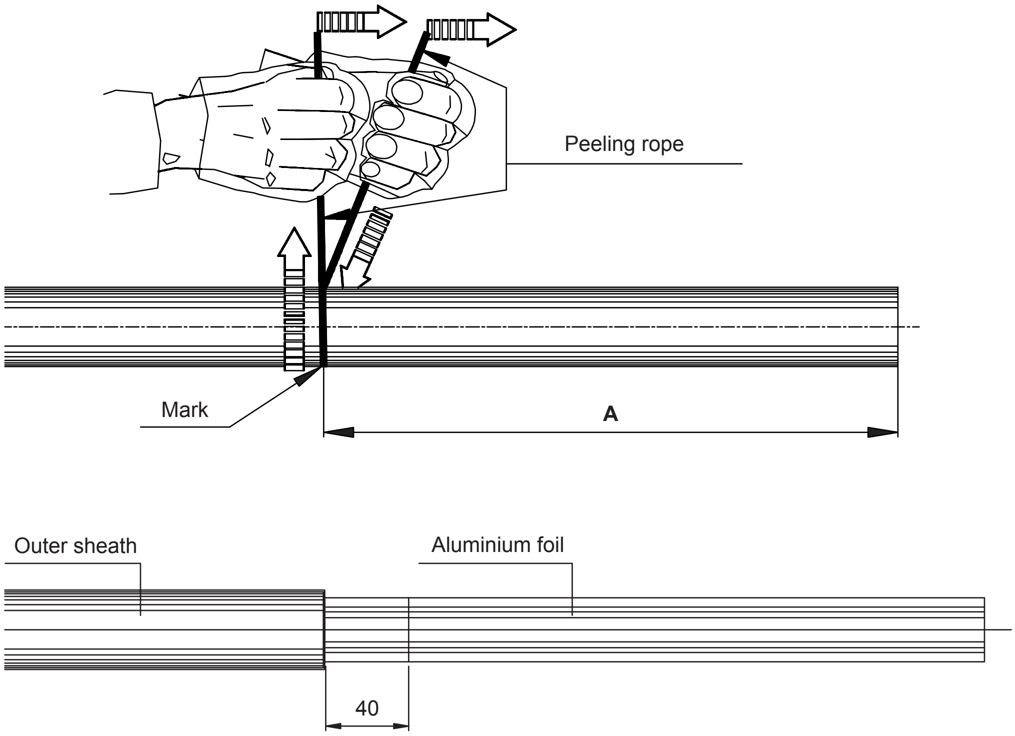
Table 1

CABLE PREPARATION DIMENSIONS

Kit	Um kV	Cable size mm²	Outer sheath removal A mm	Max. connector dimensions	
				length mm	diameter mm
HJW11.2402	24	25-95	280	90	25
HJW11.2403	24	95-240	300	130	33
HJW11.2404	24	150-300	330	180	38

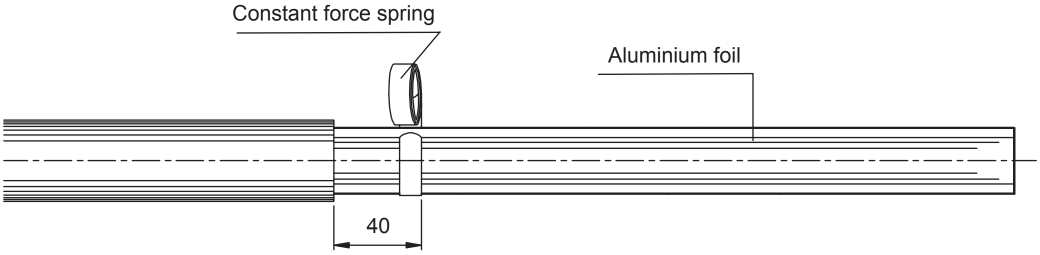


3. Heat the outer sheath up to the mark.

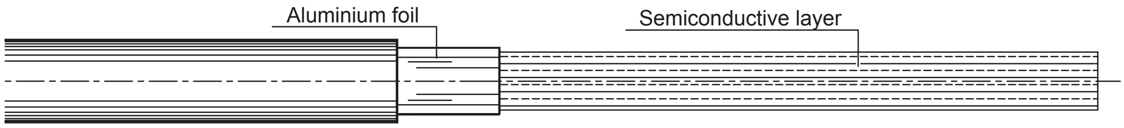


4. Use the peeling rope to remove the outer sheath to leave the aluminium foil exposed. Heat the aluminium foil close to the outer sheath with gentle flame. Remove the most of the adhesive coating from the aluminium tape for up to 40 mm from the outer sheath by the help of the peeling rope.

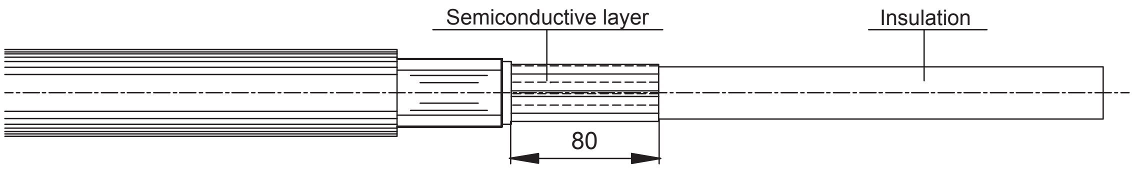
Use the grinding paper included in the kit to remove rest of the adhesive coating from the aluminium foil up to 40 mm from the outer sheath. Take care that the aluminium tape does not break during the grinding.



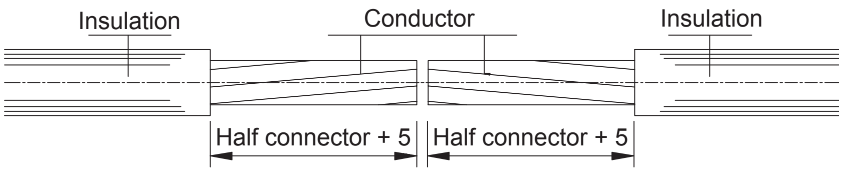
5. Install the constant force spring 40 mm away from the end of the outer sheath. Remove the aluminium foil by tearing it against the constant force spring.



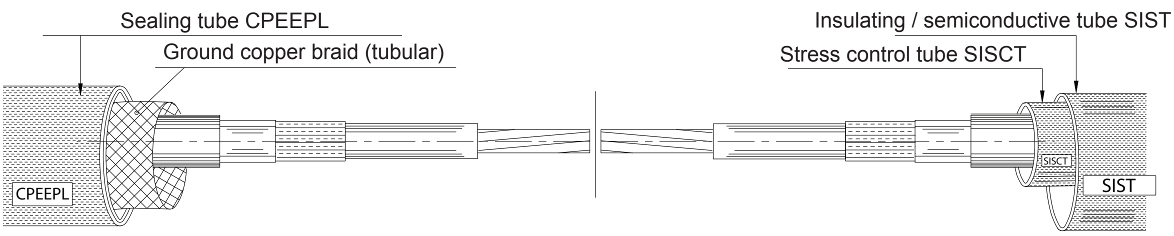
6. Move the spring a little towards the core so that the aluminium foil edge remains under the spring. Tear the swelling tape in longitudal strips up to the spring. Remove the tape strips by tearing them against the spring. Remove the constant force spring.



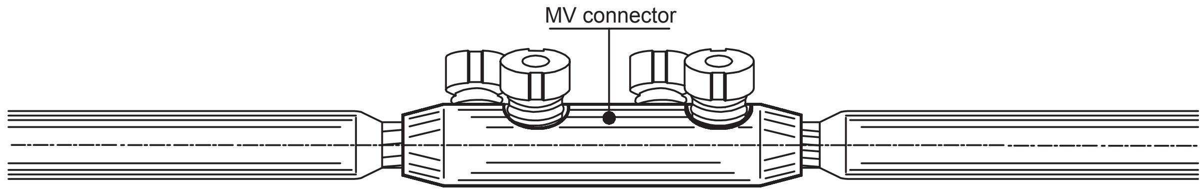
7. Remove the semiconductive layer leaving 80 mm measured from the aluminium foil. Use a suitable tool. If necessary, remove any remaining of the semiconductive layer with a piece of glass. Use the grinding paper included in the kit to smooth the insulation.



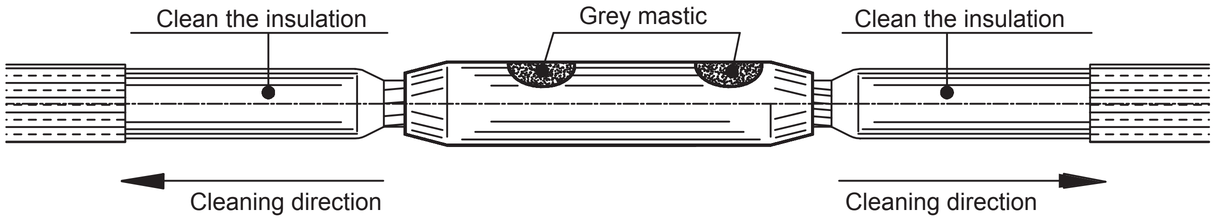
8. Remove half of the bolt connector length + 5 mm from the insulation of the cable. If you use compression connectors, remove the insulation following the connector manufacturer's instructions. Be careful not to nick the conductor. Clean the conductors and wrap a couple layers of PVC tape on the ends of the conductor.



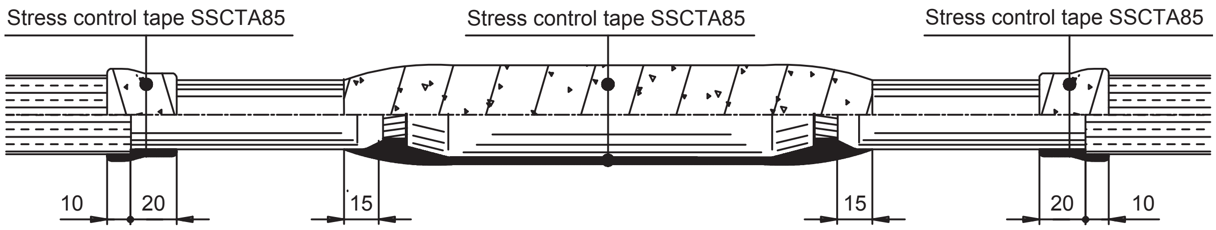
9. Slip the stress control tube SISCT, the insulating / semiconductive tube SIST and the sealing tube CPEEPL on the cables.



10. Remove the PVC tape from the ends of the conductors and install a suitable connector following manufacturer's instructions. Remove any sharp edges. Fill the holes left in the connector with grey mastic.

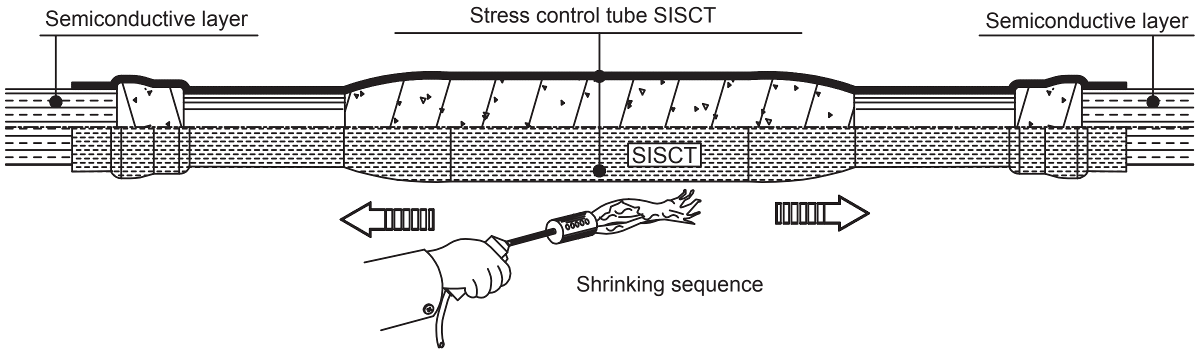


11. Clean the cable insulation with a cleaning tissue. Go towards the semiconductive layer and finally clean the semiconductive layer without touching the insulation, thus no semiconductive particles are deposited on the insulation. Clean the connector.



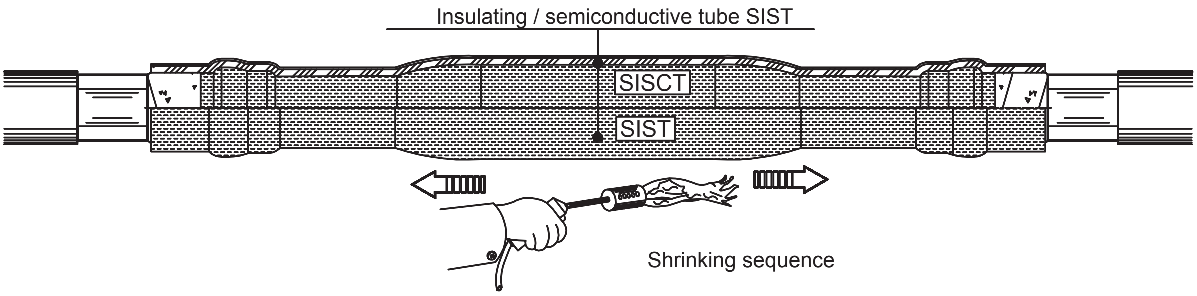
12. Fill the gap between the end of the connector and the insulation with stress control tape SSCTA85. Then apply two layers of stress control tape SSCTA85 to cover the connector. Continue up to 15 mm on the insulation on either side. Stress control tape SSCTA85 must be wrapped with a 50 % overlap and by stretching it to half of its original width.

Wrap two layers of stress control tape SSCTA85 over the semiconductive layer edge. Wrap stress control tape SSCTA85 on 10 mm of the semiconductive layer and 20 mm on the insulation. Start from the semiconductive layer. Stress control tape SSCTA85 must be wrapped with a 50% overlap and by stretching it to half of its original width.

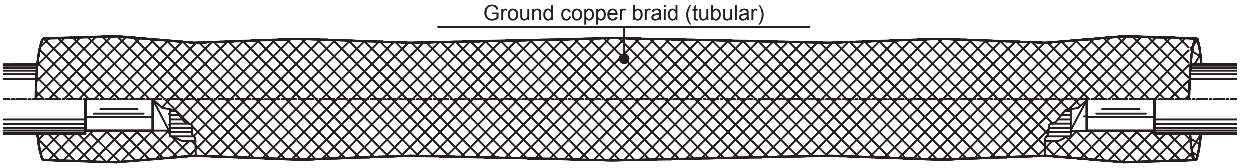


13. Centre the SISCT stress control tube on the connector. Ensure that the stress control tube overlaps the semiconductive layer on both sides of the joint. Start shrinking the tube from the middle and move towards the ends. Clean the surface of the stress control tube with a cleaning tissue after shrinking.

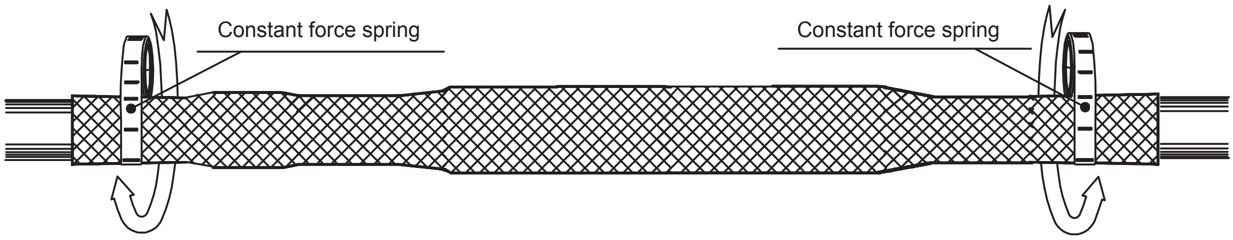
14. Fill the gap between the aluminium foil and the stress control tube by two layers of sealing mastic SSM75 on both sides of the joint.



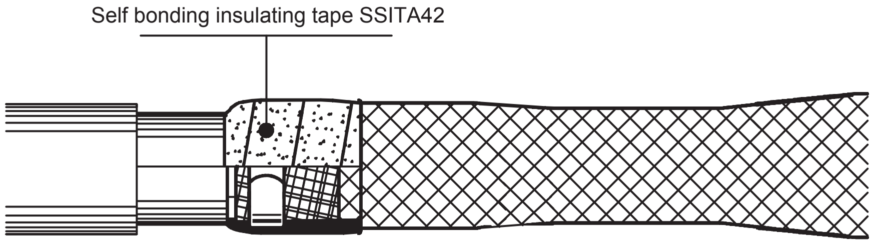
15. Centre the SIST heat shrinkable insulating / semiconductive tube on top of the stress control tube. Start shrinking it from the middle and move towards the ends.



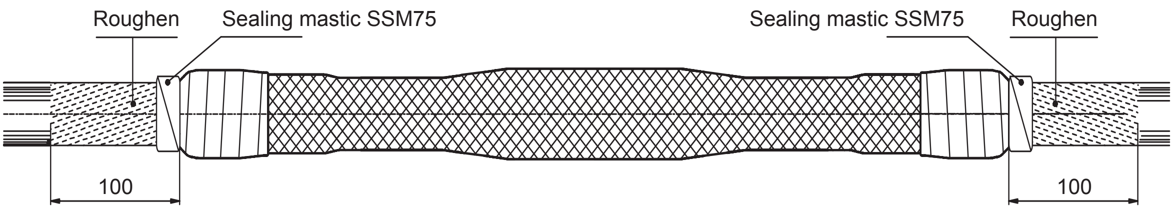
16. Centre the tubular ground copper braid on the joint.



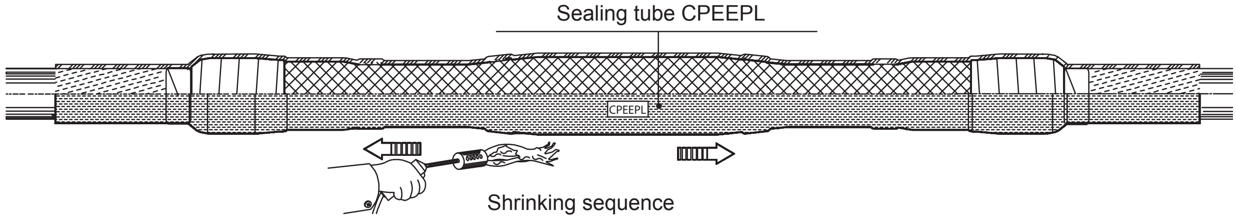
17. If necessary, fix the braid temporarily with some PVC tape. Fix the other end of the braid with two turns of the constant force spring. Fold the braid end over the spring, and turn the rest of the spring on the braid. Draw the braid to the other side of the joint so that it fits tight on the joint, and fix its end the similar way as the other end.



18. Wrap sone layers of self-bonding insulating tape SSITA42 on the constant force springs and the ground copper braid wires to smooth the sharp edges. Take care that the ends of the braid wires are fully embedded in the taping. Self bonding insulating tape must be wrapped by stretching it a bit. Wrap the tape to the direction, which tightens up the constant force spring.



19. Roughen around 100 mm of the outer sheath on both sides of the joint with grinding paper. Treat the roughened parts gently with flame. Cover the exposed aluminium tape with some layers of sealing mastic SSM75.



20. Centre the CPEEPL sealing tube on the joint. Start shrinking the tube from the middle and move towards the ends. The tube is properly shrunk when the adhesive starts coming out from the ends.

21.	The joint is finished and ready to use, but let it cool down before loading it mechanically.
22.	Join the separate earthing conductor of the cable with the LV connector included in the kit.

NOTES

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