Surface Discharge Phenomena in Medium Voltage Terminations

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ABSTRACT OF THE
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Medium voltage terminations are used in the underground cable network to connect the cables to other accessories or equipment. Secondary outdoor substations are one common place where the terminations are used in. The operating conditions inside these unheated outdoor enclosures can become extremely harsh, because of airborne contaminants and condensed moisture. The contaminants and moisture generate a conducting layer over the termination surface which can eventually lead to electrical discharges on the surface. The aim of this thesis was to study the behavior of these discharges and to compare the performance of different terminations types. The work was done by analyzing field inspection results of existing medium voltage terminations and by performing laboratory tests.

Keywords: underground cable, medium voltage, termination, partial discharge, surface discharge, dry band arcing, salt fog test

AALTO-YLIOPISTO **DIPLOMITYÖN**
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Keskijännitekaapelipäätteitä käytetään maakaapeliverkossa kaapeleiden liittämiseen muihin varusteisiin tai laitteistoihin. Puistomuuntamo on yksi yleinen kaapelipäätteen käyttökohde. Puistomuuntamon kaltaisessa ulkona sijaitsevassa lämmittämättömässä kotelossa käyttöolosuhteet voivat olla hyvinkin haastavat saasteiden ja kondensoituvan kosteuden takia. Saasteet ja kosteus luovat kaapelipäätteen pinnalle johtavan kerroksen joka voi johtaa sähköisiin purkauksiin päätteen pinnalla. Tämän diplomityön tarkoituksena oli tutkia tätä pintapurkausilmiötä ja vertailla erilaisten kaapelipäätteiden suoriutumista haastavissa olosuhteissa. Työ toteutettiin analysoimalla kenttätarkastuksista saatuja kaapelipäätteiden tuloksia ja tekemällä erilaisia laboratoriokokeita.

Avainsanat: maakaapeli, keskijännite, kaapelipääte, osittaispurkaus, pintapurkaus, suolasumutesti

AALTO-UNIVERSITET **SAMMANDRAG AV**
HÖGSKOLAN FÖR ELEKTROTEKNIK **DIPLOMARBETET**

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Mellanspänningskabelavslut används i kabelnätet för att koppla ihop kablar och annan utrustning. Parktransformatorstationen är en allmän omständighet där kabelavslut används i. Förhållanden inne i parktransformatorstationerna kan vara väldigt svåra för kabelavsluten, på grund av olika föroreningar och fukt. Kombinationen av dessa två element skapar ett ledande skikt på ytan av kabelavslutet, vilket kan eventuellt leda till glimmning. Målet med detta diplomarbete var att forska glimmningsfenomenet och jämföra olika kabelavslut som utsätts för svåra förhållanden. Arbetet utfördes genom att analysera fältgranskningsresultat för olika kabelavslut och genom att göra laboratorietester.

Nyckelord: jordkabel, mellanspänning, kabelavslut, partiell urladdning, glimmning,

Preface

I would like to thank my supervisor Professor Matti Lehtonen for the guidance with the whole thesis process. I would also like to thank my instructor Timo Vikman for providing guidance in the writing of this thesis.

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Vantaa 14th November 2015

Kenneth Väkeväinen

Contents

Abbreviations and symbols

Abbreviations

AC	Alternating current
CENELEC	European committee for electrotechnical standardization
DC	Direct current
EPDM	Ethylene propylene diene monomer rubber
FeO	Ferric oxide
HD	Harmonization document (IEC)
HV	High voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
PD	Partial discharge
PDIV	Partial discharge inception voltage
PVC	Polyvinyl chloride
RH (%)	Relative humidity
SF6	Sulfur hexafluoride
SiC	Silicon carbide
TDR	Time-domain reflectometry
ZnO	Zinc oxide

Symbols

A	Disconnector
B	Load break switch with current limiting fuse
C	Circuit breaker
E	Electric field (vector)
E_n	Electric field perpendicular component
E_t	Electric field surface aligned component
E_s	Electrical stress
U_i	Inception voltage
U_m	Maximum voltage
U_0	Phase voltage
α	Angle
ε	Permittivity
ε_r	Relative permittivity

1 Introduction

The use of underground cables continues to grow as a result of urbanization. In addition to this, traditional overhead lines are also replaced by cables to decrease the fault frequency in the network. The general expectation of these insulated cables is that they will provide faultless service for many decades. The lifetime expectancy is based on the previous generations of cables that have already provided such service. The customers see therefore no reason to accept any lesser performance. [1]

Cable accessories like terminations and joints are needed to connect the cables to the other components of the network. The inherent complication with accessories is that they have to finally be assembled in the field, where the conditions are less controlled than at the factory environment where the cables are manufactured in. This also means that the accessories are by far the most vulnerable part of the whole cable system. [1]

The joints which are mainly buried underground with the cables are generally not subjected to largely varying environmental conditions, whereas the terminations can be exposed to a wide range of different operating environments. Exposure to weather and pollution are the two most significant environmental factors that inevitably lead to electrical activity on the surface of the termination. [1]

The reasons for surface discharges and the discharge phenomenon itself is not very well known by the people working in the field, regardless of the fact that discharges are more or less common in terminations operating in outdoor environments.

The aim of this work is to study the surface discharge phenomena in medium voltage terminations and to compare the performance between different terminations types. The main focus is in the discharge occurrence in terminations located inside unheated outdoor enclosures, such as secondary outdoor substations.

The work is divided into three main sections. The first part includes a theoretical study of the medium voltage terminations, surface discharges and secondary outdoor substations. A case study is done in the second part based on a collection of fault statistics obtained from different network utilities from real network environments. In the third part different materials and termination types are compared in laboratory tests.

2 Background theory

Medium voltage cables are mainly used as a part of the distribution network, to deliver electricity between the high and low voltage systems. Medium voltage networks are used as a link between these two systems, since the use of only one high voltage system to supply the low voltage networks directly would lead to extremely high costs and other problems. The medium voltage system provides also a convenient voltage level for directly connecting large industrial loads or other larger buildings and office blocks. [2]

Medium voltage terminations are used in the cable networks in various applications and operating environments to connect the underground cables to transformers and other auxiliary equipment.

2.1 Medium voltage terminations

A termination is a cable accessory used to prepare the end of a cable to provide sufficient electrical and mechanical properties. [3] The main function of a termination is to electrically connect the insulated conductor to another connection point (e.g. a busbar). The termination should also prevent water from entering the cable and provide mechanical cover to the cable end. The cable and the termination form a combined system, so the terminations have to withstand the same electrical stresses as the cable does. [4]

When a medium or high voltage cable with an insulation screen is cut, the cable needs to be terminated to withstand the electrical field strength concentration caused by the changed geometry. The electrical field strength inside the cable remains constant as long as the cable maintains the same physical dimensions. When the cable is cut, the electrical field strength is concentrating at the end of the cable between the conductor and the screen. [3]

The installation of cable accessories requires the removal of the insulation screen from a suitable length from the end of the cable. [5] This is done to reduce the electrical field strength and to provide sufficient leakage distance between the conductor and the screen. The distance varies for different termination types based on the system voltage, stress control technique and operating environment. The removal of the insulation screen disrupts the cable’s coaxial electrode structure which causes critical electrical field strength at the cut edge of the screen (Figure 1). This stress could lead to partial discharges in the insulation or in air. Some type of stress control (or grading) is required in most medium voltage applications, to prevent partial discharges from causing electrical degradation of the materials at the cut edge of the insulation screen. [3]

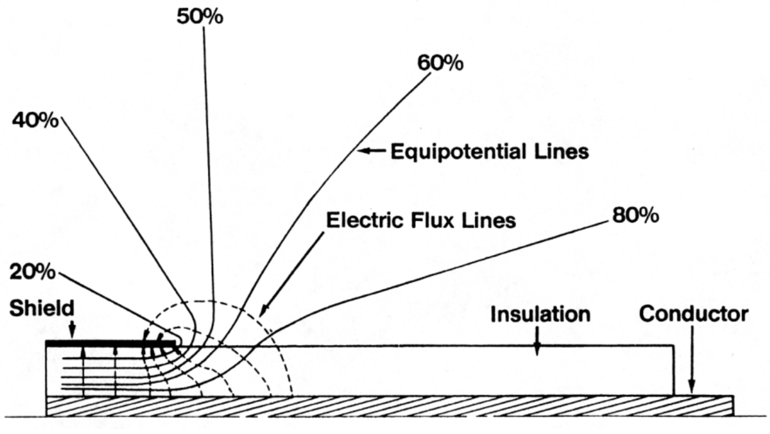


Figure 1: Voltage distribution in a termination without stress control [6]

2.1.1 Stress control techniques

To produce a medium voltage termination where the electrical field strength is kept below the breakdown level of the insulation, some sort of stress control is required at the cut edge of the insulation screen. [3]

The traditional method of reducing the electrical field strength is done by using geometrical stress control (Figure 2). [3] This can be done by optimizing the geometry of the electrodes since the equipotential lines follow the electrode shape. [5] In practical applications it means that a cone shaped layer of insulation with a conducting top layer (stress cone) is added over the cable insulation at the cut edge of the screen. [7] The stress cone provides additional insulation thickness at this high stress area and therefore also decreases the electrical field strength by increasing the distance between the conductor and the edge of the screen. The electrical field strength at the edge of the screen decreases when the ground electrode moves gradually away from the conductor. [3] The stress cone also provides a smoother potential distribution in the outer insulating layers. [5]

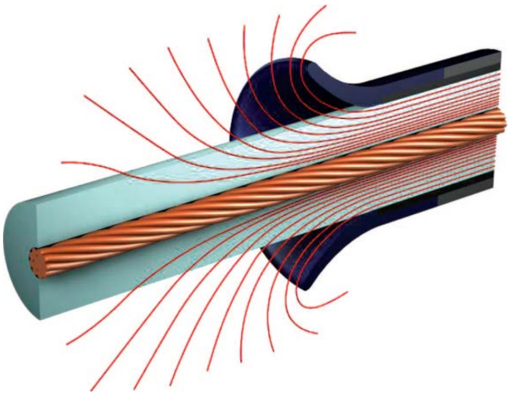


Figure 2: Geometrical stress control cone [5]

A stress cone can be pre-molded or made by taping a conical configuration of insulating tape, with a conducting top layer connected to the insulation screen. The conventional shape of a stress cone is to have the initial angle close to zero degrees and then to follow a logarithmic curve along its length. This shape provides the ideal solution but is not normally required in medium voltage cables. A straight slope with an angle of 3 to 7 degrees is generally used in hand built terminations. The total insulation thickness in the hand built terminations is generally about twice the cable's insulation thickness at the top of the cone. [3]

Another type of geometrical stress control can be achieved by applying a combination of insulating and conductive layers on top of each other at the area of highest electrical stress. A potential difference is generated between two conducting layers by the capacitive coupling and the overall electrical field strength can be adjusted by the amount of conductive layers. This technology is used in bushings and tapered joints where individual insulating and conducting layers are wrapped around the cut edge of the screen. [5]

Refractive stress control provides another commonly used stress control method for cable accessories. The method can be applied in various ways, but the main idea is to use non-conducting materials with high dielectric constant, ε_r (permittivity). In practice it means that a layer of material with high permittivity is added on areas with high electrical stresses. This can for example be achieved by wrapping tapes around the cable at the cut edge of the insulation screen. Another solution is to incorporate refractive features in materials like polyethylene, silicon or EPDM rubber, which can then be pushed or shrunk to the desired position over the cable. [5]

Regardless of what the used application technique is, all refractive stress control methods have in common that the permittivity of the refractive material (ε_{r2}) is significantly higher than what the cable insulation (ε_{r1}) and the surrounding material (ε_{r3}) have, according to Equation 1. [5]

$$\varepsilon_{r2} > \varepsilon_{r1} \geq \varepsilon_{r3} \tag{1}$$

With angles other than 90° the direction of an electric field vector (E) is refracted at the interface between two materials with different permittivity values, as demonstrated in Figure 3. In situations where it can be assumed that the conductivity of the insulation is zero (often with alternating current and impulse voltage) the refraction is determined exclusively by the relationship between the two materials permittivity (Equation 2). [7]

$$\frac{tan\alpha_1}{tan\alpha_2} = \frac{E_{n2}}{E_{n1}} = \frac{\varepsilon_1}{\varepsilon_2} \tag{2}$$

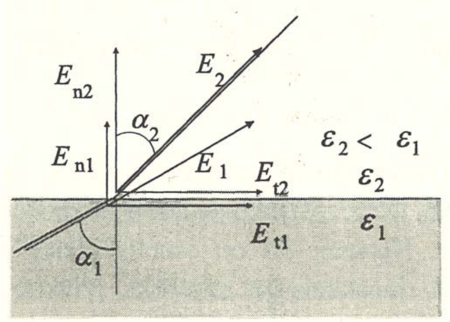


Figure 3: Refraction of the electric field between two dielectrics [7]

The material with a lower permittivity is subjected to a higher electrical stress in layered insulation structures. [7] Based on the refraction relationship with different permittivity values between materials, the ratio of the electrical stresses in the cable insulation (ε_{r1}) and the surrounding material (ε_{r3}) can be adjusted by applying a material with higher permittivity between them (ε_{r2}). In cable terminations this means that the high electrical field concentration at the cut edge of the insulation screen can be moved further away from the edge and spread more uniformly between the cable insulation and the surrounding material (Figure 4). [5]

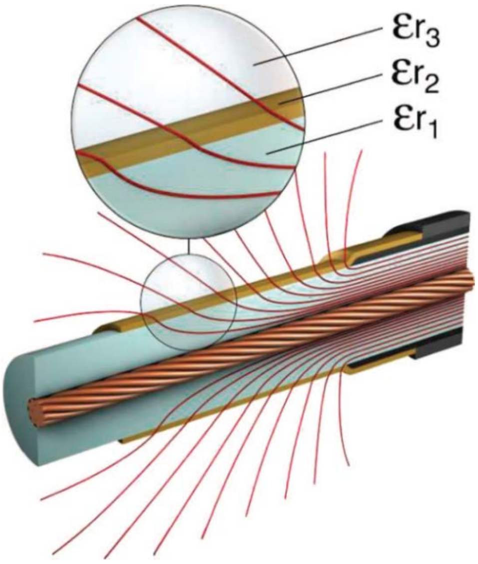


Figure 4: Refractive stress control [5]

When an electric field is applied over an insulating material, the positive and negative parts of the atoms and molecules are subjected to a force that displaces them from their normal state. This phenomenon is known as polarization. The polarization changes its direction when an alternating current is applied over the material and dielectric losses are generated by the friction in the material. [7]

The dielectric losses in refractive materials cause some limitations for the use of the refractive stress control technique. The loss increases when the permittivity or the volume of the material is increased. Also the frequency affects the dielectric loss in the material. In order to avoid local overheating, sufficient heat transfer needs to be taken into consideration when cable accessories with refractive stress control are designed. [5]

The impedance stress control technique offers another common method for controlling the electrical field strength in cable terminations. The application of this technique is managed in the same way as with the refractive method, by using shrinkable tubes or patches at the edge of the insulation screen. A specific resistivity in the applied material allows the adjustment of the electrical field distribution in the termination. The cable itself is a cylindrical capacitor and the stress control is achieved by combining this capacitance with the material properties of the applied stress control material at the edge of the insulation screen (Figure 5). [5]

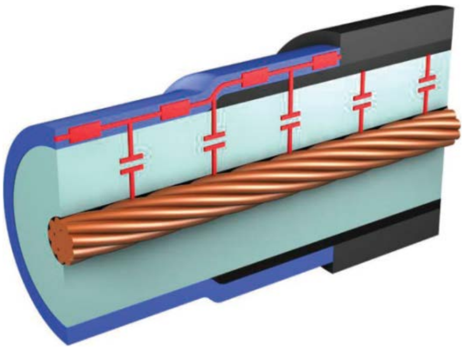


Figure 5: Equivalent circuit of a cable end covered by the impedance stress control material [5]

Successful use of this technique requires suitable impedance in the applied material. In case of a highly insulating material the situation is similar to when no stress control is used. The highly insulating material leads to a high electrical field concentration at the edge of the insulation screen. The situation is also unsatisfactory with a highly conductive material as the electrical field strength is not reduced but instead it moves to the edge of the applied material. A working solution therefore requires that the conductivity in the stress control material is somewhere between these two cases (Figure 6). [5]

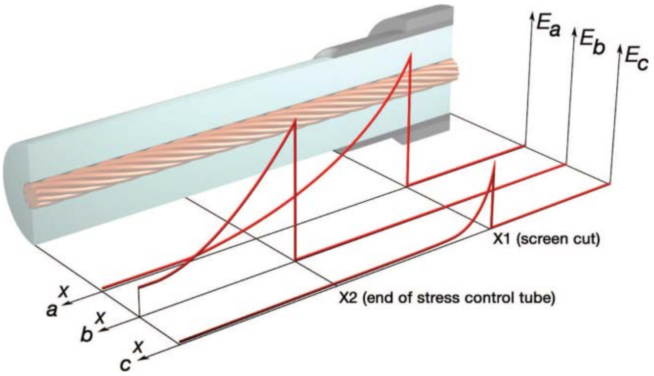


Figure 6: Electric field distribution as a function of position between ground and HV electrode. a) insulating material, b) conducting material and c) optimized impedance stress control material [5]

The stress control material consists of an insulation base material which conductivity is adjusted by conductive additives like carbon black. The resultant polymer conductivity of the stress control material needs to be in the range of 10^{-5} to 10^{-10} S/cm in order to achieve working stress control for cable terminations. [5]

One of the main advantages of the impedance stress control technique, compared to other methods, is the slim and compact design of the accessories. [5] Then again it is important to note that the frequency of the applied voltage affects the function of the stress control and the electrical field distribution can vary significantly with direct current (DC) and alternating current (AC). Since DC testing is still more or less common in field tests, the security of the insulation should be assured before performing tests for cable accessories with impedance stress control. [7]

The nonlinear stress control method is amongst the newest developments for stress control systems. The main idea is to use a nonlinear material whose resistivity vary based on the applied voltage. This system is based on a compound formulated from polymer and an additive that provides the nonlinear electrical properties. Different additives like silicon carbide (SiC), ferric oxide (FeO) and zinc oxide (ZnO) can be used. The stress control compound can be extruded or molded, so the application of the stress control material can be managed using various different end products like heat-shrinkable tubes, coatings, tapes and patches. [5] [8]

The stress control material provides nonlinear characteristics with a certain threshold voltage, similar to that provided by diodes and varistors. If the applied voltage is lower than the threshold voltage, the material operates as a linear insulator. When the threshold voltage is exceeded the conductive paths in the material become active and the electrical field strength is kept fairly constant throughout the whole stress control material. [8] The electrical stress can be limited to a certain level (E_s) in a cable termination, by placing a cylindrical stress control layer over the edge of the insulation screen. [5] In terminations the electrical stress is always limited according to the threshold voltage of the material and a longer distance of stress control is therefore activated for higher voltages (Figure 7). [8]

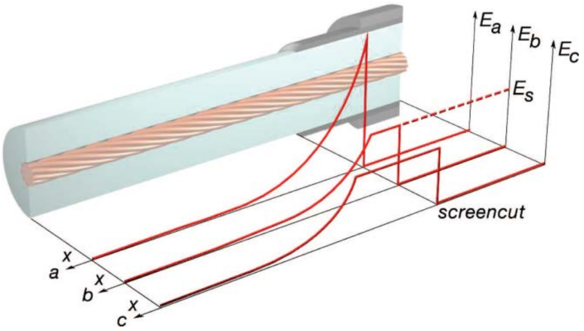


Figure 7: Electric field distribution as a function of position between ground and HV electrode with nonlinear stress control. a) without stress control, b) with nonlinear stress control, c) nonlinear stress control and a higher voltage [7]

One of the main advantages of the nonlinear stress control technique is its excellent electrical stress distribution along the termination. It also prevents overstresses of the material and handles well electrical impulses, such as external overvoltage and transient voltages. [8]

Manufacturers of cable accessories rely on different stress control techniques based on the requirements of their customers. All techniques have their benefits and restrictions and none of them offers a universal solution for all applications. For example electrical performance, cost, design and ease of installation are all aspects which influence the choice of a certain accessory type and different stress control techniques.

2.1.2 Termination types

Medium voltage terminations are generally classified based on the rated voltage of the accessory and the operating environment where the termination is to be used. The environmental classification divides the terminations into two main groups, indoor and outdoor terminations. CENELEC’s harmonization document HD629.1 defines the general test requirements for medium voltage accessories used on extruded cables. This document defines the two termination types as following:

- **Indoor termination:** Termination intended for use where it is not exposed to either solar radiation or weathering.
- **Outdoor termination:** Termination intended for use where it is exposed to either solar radiation or weathering or both. [9]

The IEEE has gone further in the classification of terminations in their IEEE Standard 48, which defines the test procedures and requirements for medium and high voltage AC cable terminations. In this standard the indoor and the outdoor terminations are divided into two additional subgroups:

- **Indoor termination-dry:** A termination intended for use where it is protected from solar radiation and precipitation and not subject to periodic condensation, or other excessive humidity (90% RH or more). May be installed in air conditioned or heated areas.
- **Indoor termination-wet:** A termination intended for use where it is protected from direct exposure to both solar radiation and precipitation, but is subjected to climatic conditions that can cause condensation onto the termination surfaces.
- **Outdoor termination:** A termination intended for use where it is not protected from direct exposure to either solar radiation or precipitation.
- **Outdoor termination-polluted:** A termination intended for use where it is not protected from direct exposure to either solar radiation or precipitation, and is exposed to nonstandard (unusual) service conditions such as extreme seacoast salt deposits, solid precipitates, etc. Often requires extra maintenance such as washing or extra creepage length. [10]

Indoor terminations

Indoor terminations are expected to be installed in a dry environment where they are protected from sunlight and precipitation. The terminations should not be subjected to condensation or excessive continuous humidity and should also be protected from wind driven pollutants. This kind of environmental exposure can be expected to be found for example in substations located inside office or industrial buildings. Rain sheds are generally not needed at all in terminations operating in dry environments. [10]

The IEEE 48 standard specifies also the indoor termination type for environments where moisture can be present. This type of termination is protected from exposure to sunlight and precipitation, but can be subjected to climatic changes that cause condensation on the termination surface and infiltration of wind-driven particles settling on these surfaces. This kind of environmental exposure could be expected to be found for example in free-standing outdoor enclosures. The standard does not specify any additional test requirements for this type of wet indoor terminations but designs with rain sheds should be considered. [10]

Outdoor terminations

Outdoor terminations are expected to be installed in an environment where they are not protected from solar radiation, airborne pollutants or precipitation. [10]

The IEEE 48 standard includes a pollution severity guide with four different environment types where outdoor terminations are to be used. The guide is meant to assist the user to broadly define the environment in which the terminations are to be installed.

- **Light:** Areas without industries and with low-density housing. Areas subjected to frequent winds and/or rainfall with low-density of industries or housing. Also agricultural and mountainous areas. These regions should be situated approximately 10 – 25 km from the coast and should not be subjected to coastal winds. The distance depends on the topography of the coastal area and the extreme wind conditions. Outdoor terminations with rain sheds are recommended for these environments.
- **Medium:** Nonpolluting industrial areas subjected to infrequent rainfall and/or average housing. Also areas with frequent winds and/or rainfall with high-density industries and/or housing. Areas exposed to coastal winds but generally located further than 3 km from the coast. The use of fertilizers by spraying, or burning of crop residues can lead to higher pollution levels. Outdoor terminations with rain sheds are generally used in these environments.
- **Heavy:** High-density industrial areas and urban areas with high-density housing, especially areas with infrequent rainfall. Areas subjected to moderate concentration of conductive dust, particularly industrial smoke producing deposits. Areas close to the coast that are exposed to coastal spray or strong winds carrying sand and salt, and subjected to regular condensation. Outdoor terminations with rain sheds are mainly used. A termination of a higher voltage level or extended creepage distance should be considered if the area has a known history of contamination related problems.
- **Extremely heavy:** Usually very limited areas with extremely heavy pollutants from industrial sites, especially those located close to oceans and subjected to winds from the sea. Small isolated areas where the terminations are located next to a pollutant source like cement plants, paper mills or other similar sources. Outdoor terminations of next voltage level or with additional creepage distance are normally required. Also extra maintenance such as periodic washing is often needed. [10]

Pollution classes in insulators

Similarly to the pollution severity guide, classification based on pollution class is also used for high voltage insulators. The IEC60815 standard defines four different pollution classes and also gives a recommendation of the creepage distance along a phase to earth surface, where the voltage is given as maximum line voltage, U_m. The definition of each class is basically the same as the classes defined for outdoor terminations. [7] Recommended creepage distances for different pollution classes are mentioned below:

- I – Light: 16 mm/kV
- II – Medium: 20 mm/kV
- III – Heavy: 25 mm/kV
- IV – Extremely heavy: 31 mm/kV

Based on these recommendations, the dimensions for some traditional voltage ratings used in medium voltage cable terminations are given in Table 1.

Table 1: Recommended creepage distance for different pollution classes

Rated voltage [kV]	Class I [mm]	Class II [mm]	Class III [mm]	Class IV [mm]
6/10 (12)	192	240	300	372
12/20 (24)	384	480	600	744
18/30 (36)	576	720	900	1116
20,8/36 (42)	672	840	1050	1302

2.1.3 Service conditions

The standard service conditions for cable terminations are specified in the IEEE 48 standard. The temperature of the surrounding air in direct contact with the termination should be between -30 ˚C and 40 ˚C. The temperature inside an enclosure where the termination is located can however be higher but should not exceed 55 ˚C and the temperature of the equipment or busbar to which the termination is connected to should not exceed 85 ˚C at full load. The altitude should not exceed 1000 meters. [10]

The following environmental conditions are mentions in this standard as nonstandard service conditions which may require special consideration in design or application of the termination:

- Temperature values outside of the standard values
- Altitudes exceeding 1000 meters
- Damaging fumes or vapors, excessive or abrasive dust, explosive mixtures of dust or gases, steam, salt spray, excessive moisture or dripping water, salt on roadways and other similar pollutants
- Unusual mechanical conditions such as vibrations, shock, cantilever loading, wind or icing
- Unusual transportation or storage conditions
- Unusual space limitations
- Unusual internal pressures
- Unusual maintenance difficulties [10]

2.1.4 Test requirements for terminations

Medium voltage terminations are installed in a range of varying operating environments from very mild to extremely severe. The designed electrical withstand level of a termination can become significantly lowered, as airborne pollutants are mixed with water. Indoor and outdoor terminations have different test requirements and suitable accessories should be chosen correctly based on the environment in which they are to be installed. [10]

The tests for the cable terminations in HD629.1 S2 are divided into three different test sequences; A1, A2 and A3. The A1 test sequence is the basic test for terminations which includes general electrical tests to verify the functionality of the stress control and also general performance of the accessory during long time ageing. The A2 test sequence includes short-circuit tests for the conductor and the screen in order to verify the performance during faults in the network. The purpose of the A3 test sequence is to verify the environmental performance of indoor and outdoor terminations. [9]

Comparison of test requirements

The A1 test sequence in HD629.1 is almost the same for indoor and outdoor terminations with the only difference that outdoor terminations are subjected to an additional immersion test and an AC voltage wet test. The immersion test is basically a water tightness test for the accessory and in the AC voltage wet test water is sprayed on the termination while a voltage of $4U_0$ is applied for 1 minute. [9]

Table 2: A1 test sequence for indoor and outdoor terminations

Test	Indoor	Outdoor	Test requirements
DC voltage dry	x	x	*15 min at 6 U_0*
AC voltage dry	x	x	*5 min at 4.5 U_0*
AC voltage wet		x	*1 min at 4 U_0*
Partial discharge at ambient temperature	x	x	*10 pC at 1.73 U_0*
Impulse voltage at elevated temperature	x	x	*10 impulses, each polarity*
Heating cycle voltage in air	x	x	*126 cycles at 2.5 U_0*
Immersion		x	*10 cycles*
Partial discharge at elev. and amb. temp.	x	x	*10 pC at 1.73 U_0*
Impulse voltage at ambient temperature	x	x	*10 impulses, each polarity*
AC voltage dry	x	x	*15 min at 2.5 U_0*
Examination	x	x	*For information only*

The A2 test sequence is identical for both termination types. The main difference in the test sequences between these two termination types is in the A3 test sequence where the environmental performance is tested.

Indoor terminations are subjected to a humidity test where the terminations are placed inside a test chamber equipped with spray nozzles or other form of humidifiers. Atomized water with a conductivity of $70 \pm 10\, mS/m$ is then discharged into the chamber throughout the whole test, at a rate of $0.4 \pm 0.1\, l/h/m^3$. The test cables are energized with a voltage equal to $1.25U_0$ and the test is run for 300 hours. [11] The requirement is that the performance of the accessory should not be severely reduced during the test due to tracking, erosion or other kind of degradation of material. [9]

Outdoor terminations are subjected to a salt fog test which is performed in a similar chamber than the humidity test for indoor terminations. The difference in the salt fog test is that the conductivity of the water is $1600\ \pm\ 200\, mS/m$ and the duration of the test is 1000 hours instead of 300 hours. [11] The requirement in this test is the same as in the humidity test. [9]

Table 3: A3 test sequence for indoor and outdoor terminations

Test	Indoor	Outdoor	Test requirements
Humidity test	x		*300 h at 1.25 U_0*
Salt fog		x	*1000 h at 1.25 U_0*
Examination	x	x	*For information only*

2.1.5 Installation technologies

Another common method for identifying different cable accessories from each other can be done by dividing them based on the used installation technology. Two commonly used applications in range-taking cable accessories with extruded cables are heat-shrink and cold-shrink technology and various combinations of these two. Other types of premolded accessories and separable connectors are also available, but the range of these products is generally limited to narrower cable diameters. Also the use is limited to more specific applications, so they will not be discussed more closely in this work. [12]

Heat-shrink technology

Heat-shrink technology uses polymeric materials that have been extruded or molded into a desired shape, generally a tube. The product is then subjected to crosslinking by a radiation beam or by chemical means. After crosslinking, the product is expanded into a bigger size by first warming it up, and letting it then cool down in this expanded state. When heat is applied again the expanded product, it returns back to the shape it had during the crosslinking process (Figure 8). [12]

The heat-shrink technology was first introduced in the end of 1960’s. The technology revolutionized the whole low and medium voltage cable accessory market and several advancements have been made ever since the introduction. Most of the improvements mainly concerned the design of materials and the formulations used in single-layer tubes but dual-layer products with dual-functionality have been introduced later on. [13]

Figure 8: Heat-shrink termination installed onto a 20 kV three-core cable [14]

Cold-shrink technology

Cold-shrink technology relies on elastomeric materials used in the same manner as heat-shrinks. Like heat-shrinks, the cold-shrinks can fit a wide range of cable diameters but offer some advantages related to the assembly of the accessory. Gas bottles and torches are not needed during assembly and the installation quality is less dependent on the skill of the installer. The elastomeric material continues to shrink towards its original shape after installation and does not stop shrinking like the heat shrink does when it cools down after installation. The product can either be of stretch rubber type (slip-on) or pre-stretched in the factory on to a plastic support tube (spiral tube) for easier installation (Figure 9). [12]

Figure 9: Pre-stretched cold-shrink termination installed onto extruded 20 kV cables [15]

2.2 Surface discharges and dry band arcing

Surface discharges can occur in situations where the insulation surface is subjected to high electrical field strength. This kind of discharges are known as gliding discharges and are generated at the interface of two insulations when the electrical field component along this interface is high enough. [4] A high electrical field component perpendicular to the surface increases the possibility for gliding discharges. The most common structures where this kind of surface discharges can occur are at the interfaces between solid insulations and fluids or solid insulations and air, like in cable terminations and bushings. [7] A higher voltage leads to longer discharges along the surface. The discharges also affect the electrical field distribution and can eventually lead to a complete flashover between the electrodes.

The inception voltage U_i of the gliding discharge depends on the permittivity ε_r and the thickness of the solid insulation. The performance of such an insulation structure can therefore be improved by increasing the thickness of the solid insulation or by decreasing its permittivity. It should be noted that the inception voltage in this kind of structure is not significantly affected by the creepage distance between the electrodes. [7] Gliding discharges are generally avoided by making the electrical field distribution more uniform by well-designed stress control. [4]

Environmental conditions such as air pressure, temperature and humidity all affect the breakthrough strength of insulations and therefore also influence on the occurrence of surface discharges. The breakthrough strength increases normally when the pressure increases or the temperature decreases. [4] An increased humidity increases also the breakthrough strength in air but the situation is completely opposite when the insulating structure is generated from a parallel interface between air and a solid insulation. The increased humidity decreases the breakthrough strength along this interface because droplets are condensed at the surface. The droplets generate local points on the surface where the electrical field strength is increased. This phenomenon is even stronger when the surface is polluted by conducting particles from coastal salt, industrial dust, carbon ash or other similar pollutants. [4] [7]

The pollutants and the humidity together will increase the conductivity of the surface and leakage currents starts to flow along this surface. The leakage current can cause local heating and generate dry zones on the surface. Visible arcing, known as dry band arcing can be seen on the surface over these dry zones in certain situations. [7] Also rain decreases the breakthrough strength of insulations in the same manner as humidity does. The situation is however not as critical since intense rain can flush away pollutants from the surface and thereby decrease the leakage current. [4]

The environmental conditions and pollution should be taken into consideration when insulating structures are dimensioned, since the performance can decrease significantly in unfavorable conditions. The performance in harsh environments can generally be improved by increasing the creepage distance between the electrodes. Also cleaning of the surface at certain intervals may be needed in some cases, in order to prevent surface discharges from occurring. [4] [7]

2.2.1 Tracking and erosion

The temperature at the root of a surface discharge can be very high even if the area of the discharge is extremely small. The energy in this small area is still sufficient to break up a few molecules of the insulation and starts to slowly cause degradation of material. This degradation of material eventually leads to tracking or erosion of the insulation. [16]

Erosion is caused when the discharge destroys the molecular structure of the material but does not leave a conductive carbon residue on the surface. [16]

Tracking however occur when the heat of the discharge cause carbon particles to be left on the insulation surface. The carbon particles continue to grow and eventually create a continuous conducting path along the surface. [16]

Tracking can also occur between two materials if discharges are formed by moisture at such an interphase. The by-products from the discharge are trapped between the materials and tracking will occur. This type of anaerobic tracking can occur for example in cable terminations if rain sheds are poorly installed or when PVC tape is used for phase marking (Figure 10). [16]

Figure 10: Anaerobic tracking paths under a loose rain shed in a heat-shrink termination

2.2.2 Termination surface

Correctly chosen accessories based on the operating environment is one of the key features in order to avoid excessive surface discharges from occurring. The discharges can't generally be totally avoided in operating conditions where the terminations are subjected to moisture and pollutants. The surface of the termination plays a key role in the performance of the accessory in these situations.

Discharges can occur is situations where the surface of the termination becomes covered in a conducting layer. Moisture generated by fog, mist or rain can normally create such a layer, but the conductivity of this layer is low in clean rural areas. [16]

Terminations situated in industrial areas are often covered by a layer of dry airborne particles, which build up over a longer time. The layer has basically no effect until it becomes moist and the ionic solids are dissolved and form a well conducting layer. The situation becomes worse in cases where the termination is subjected to only condensed moisture as there is no cleaning effect. This kind of conditions can often be seen in unheated outdoor enclosures, such as secondary outdoor substations.

Terminations situated near the coast are potentially subjected to the worst operating conditions, as sea salt is combined with moisture and can generate a highly conducting layer on the surface. [16]

The conducting layer on the termination allows current to flow along the surface from the cable lug to the ground connection. If the current is high enough it will start to heat the surface and evaporate moisture. This evaporation is not uniform since the resistance along the surface is not constant. The surface resistance in the termination is generally highest at the smallest diameter or where the diameter of the profile changes and the pollution build-up is smaller. A dry area will eventually form by the evaporation around the termination, since once the drying starts, current has to pass through a smaller area which generates even more heat in that point (Figure 11). The majority of the system voltage is then applied across this area due to the voltage divider effect, once the dry band is formed. This will lead to arcing across the dry band as the breakdown strength of air is exceeded. The environmental conditions change over time and the situation is generally far from stable. A higher leakage current normally generates more discharges that will more likely move around and elongate over time. [16]

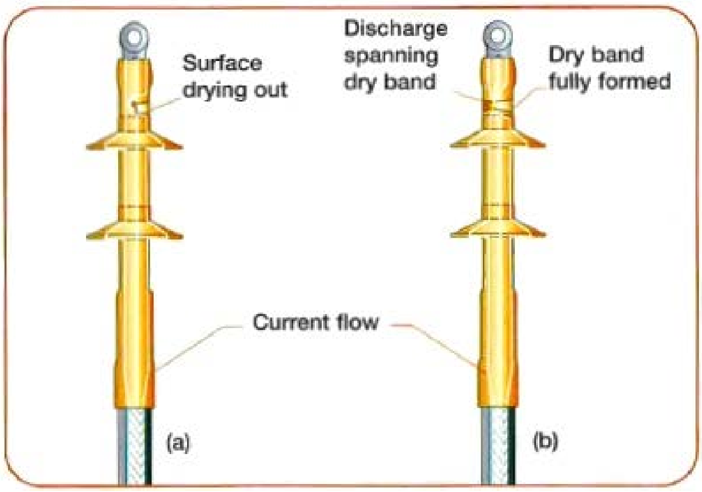


Figure 11: Dry band and discharge formation [15]

Since the terminations can't be completely protected from the pollutants the creepage distance along the surface of the termination has to be sufficient. The creepage distance is generally increased by installing additional rain sheds since the total length of the termination might be limited to a certain maximum value. [7]

The surfaces of cable terminations are also made of materials with anti-tracking properties because discharges cannot always be completely avoided. Also surface properties that help to repel moisture and pollutants can improve the performance of the accessory in harsh environments. [7]

Anti-tracking properties

The surface materials used in cable terminations include anti-tracking properties which make them more resistant to damage caused by tracking and erosion. The molecular structure in these materials does not encourage carbon formation when the surface is heated. Fillers like alumina trihydrate or magnesium hydroxide are used to improve the tracking performance of the material. Alumina trihydrate gives off steam when it is exposed to heat and therefore has a washing effect on the remaining material. [16]

The tracking resistance of insulating materials can be compared for example by the inclined plane test. The test is described in the IEC60587 standard which defines the test methods for evaluating resistance to tracking and erosion for insulating materials used in severe ambient conditions. Plane material samples are placed inclined inside a test chamber with electrodes 50 mm apart from each other, as shown in Figure 12. [17]

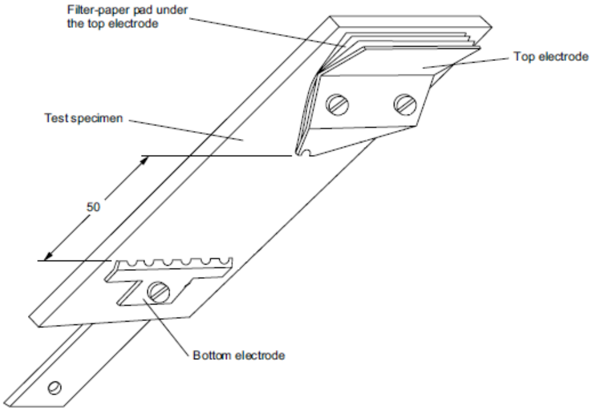


Figure 12: Test assembly for the inclined plane test [16]

Liquid contaminant with a resistivity of $3.95\,\Omega m \pm 0.05\,\Omega m$ is fed from the top so that it flows uniformly between the electrodes. A voltage between 1 and 6 kV is kept constant throughout the test or gradually increased, depending on the used test method. The samples can then be rated based on leakage current during the test or the damage caused to the material due to tracking and erosion. [17]

Hydrophobicity

The hydrophilicity or hydrophobicity describes a solid materials ability to be wet by water. Materials that are easily wet by water are known as hydrophilic and materials which naturally repel water are known as hydrophobic. The contact angle which is the angle between a liquid and a solid material appear when the material is not completely wetted. A low contact angle indicates that the surface of the material is hydrophilic and well wetting. A high contact angle again means that the surface is hydrophobic and the liquid stays as a droplet, instead of wetting the surface. [18]

A hydrophobic material thereby prevents continuous wetted areas from forming on the surface when the material is subjected to water or moisture. Because of this feature, the leakage current along the surface stays lower, as discrete droplets are created instead of wetting the whole surface. [1]

The hydrophobicity of a surface can be lost by the action of intense discharge activity. The surface generally recovers its hydrophobic properties to some extent, after a certain time when the discharge activity has stopped (Figure 13). [1] The recovery of the hydrophobic properties has received increasing attention as an important factor affecting the performance of outdoor polymer insulations. [19] Hydrophobic polymers such as silicon rubber have been successfully used in insulators located in polluted areas. [7] Silicon based grease can also be used to increase the hydrophobicity of an insulators surface. [4]

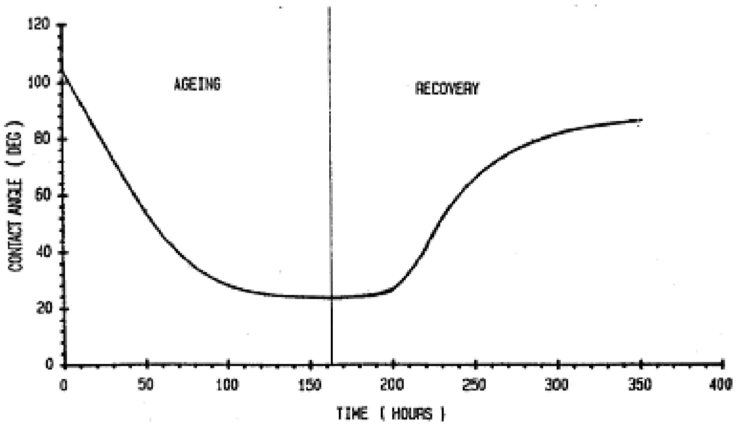


Figure 13: Recovery of hydrophobicity in a silicon insulator [20]

2.2.3 Fault diagnosing

Traces of surface discharges can usually be seen in some medium voltage terminations that are located inside outdoor enclosures. The remnants of burnt insects and bigger particles are often seen around the area where the insulations screen cut edge is located, because of the high step voltage on the surface of this area. Discharges of this type are not harmful, as long as the discharge phenomenon is not continuous and the surface of the termination stays intact. Continuous surface discharges cause degradation of material, so it is important to identify the symptoms of erratic and continuous surface discharges from each other.

The behavior and the reasons for surface discharges are generally not well known by the people working in the field and accessories have therefore been unnecessarily replaced in some cases. Correct fault diagnosing is needed in order to avoid misjudgments and also to prevent damage to the terminations and other accessories connected to them.

Visible and audible

Recognizing the symptoms of discharges by bare eye can be quite challenging when the leakage current is not high enough to generate visible or audible arcing. A dry region is visible around the termination when the humidity is high enough to develop condensation on the surface and dry band arcing is occurring. The discharges are however not constantly occurring as the environmental conditions change over time. Traces of dry band arcing can usually be seen as pale rings around the surface of the termination, as seen in Figure 14. The rings on the surface are just a byproduct of the arcing phenomenon and do not require immediate actions. The performance of the termination is not endangered as long as the surface stays intact and the arcing is not too intense to cause a complete flashover. These rings are however a clear indication of the fact that continuous discharges have been occurring and some sort of maintenance or cleaning of the terminations is required.

Figure 14: Faint marks of dry band arcing on termination surfaces

When the surface of a termination becomes moist and is covered by a well conducting layer of conducting particles, active dry band arcing can be heard and even seen on the surface (Figure 15). This type of visible arcing is not very commonly seen in the field if correct accessories are used, because the surface needs to be very conductive to achieve a high enough leakage current. Similar dry band arcing can be seen during the salt fog test for outdoor terminations where the discharges are artificially generated by spraying highly conducting salt fog on the terminations. Intensive arcing like this may seem dangerous to the accessory but the salt fog test is run for 1000 hours without extensive damage to the termination. Some maintenance actions should however be started to avoid permanent damage to the accessory.

Figure 15: Visible dry band arcing in 20 kV indoor terminations

Partial discharge measurement

Surface discharges can also be detected while performing partial discharge measurements in the field. Field measurements for medium voltage cables are generally performed off-line, by disconnecting the tested cable line from both ends to avoid disturbances from the network. The advantage of off-line measurement is that the discharge inception and extinction voltage can be obtained, because the voltage can be altered. The drawback with off-line measurement is that it always requires an outage in the network, which can be challenging to arrange in some cases. [21]

Time-domain reflectometry (TDR) is a commonly used method for partial discharge (PD) detection in cables. The main advantage of TDR is that the source for the discharge can be located along the tested cable line. Because of this feature the surface discharges in terminations can also be located. A PD signal splits into two equal signals that travel in opposite directions along the cable. The direct signal traveling towards the near end, where the measurement is performed from, is first recorded as a pulse. The other signal travels to the opposite direction and is reflected at the remote end, from where it travels back to the near end, and can be recorded as an attenuated pulse. The PD location can be estimated based on the difference between the arrival times of these two pulses, as seen in Figure 16. The third pulse in the figure represents a twice reflected attenuated pulse of the direct pulse that has traveled back and forth along the whole cable. The time difference of this pulse and the direct pulse represents the time for a pulse to travel a round-trip along the cable. [21]

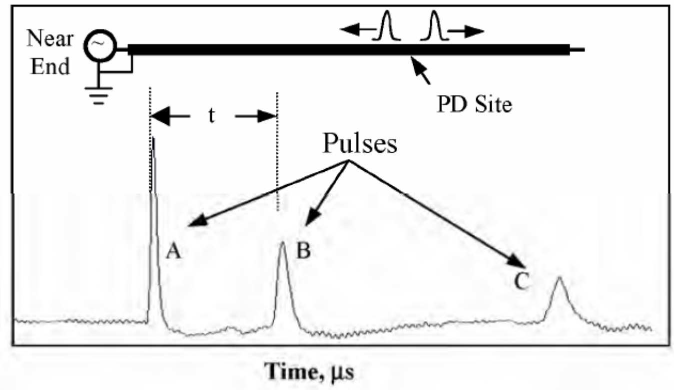


Figure 16: Principle of partial discharge measurement by time-domain reflectometry [21]

The network utilities have become increasingly interested in performing discharge measurements in their networks as the amount of underground cables increases. Field testing of medium voltage cables is however not yet very common, regardless of the increased interest and the test requirements and procedures have not been clearly standardized. Because of this, different procedures can appear in real life and the evaluation of the accessories condition is often left to the network utilities themselves. As there is no reference of what is an allowable level of partial discharge in aged accessories, the network utilities often tend to replace any accessories where discharges are detected at operating voltages.

If discharges are detected in terminations during field tests, it is extremely important to clean the terminations properly and to perform the measurement once again, in order to find out the real condition of the accessories. This kind of procedure increases the testing time but allows the identification of surface discharges and unnecessary replacement of terminations can be avoided.

Thermal imaging

Thermal imaging offers a convenient way of identifying surface discharges and dry band arcing when they are not otherwise visible or audible. The occurrence of surface discharges can easily be identified by analyzing the thermal images of terminations in normal operation. The heat generated during the evaporation process is easily recognized from the image and fault diagnosis can be done without the need for disruptions in operation. The effectiveness of thermal imaging is clearly visible in Figure 17, where the normal image and the thermal image are placed next to each other. The figure represents a 20 kV indoor three phase termination, operating inside an unheated outdoor enclosure. Two of the phases have clear hot spots caused by dry band arcing that would probably not have been recognized by bare eye. Closer inspection of the terminations revealed that the rain sheds in both faulty phases were loose, which is quite commonly seen when terminations are installed inside cramped enclosures. Since the phenomenon was in this case noticed in an early phase because of thermal imaging, the problem was easily fixed without the need for bigger repairs or replacement of accessories.

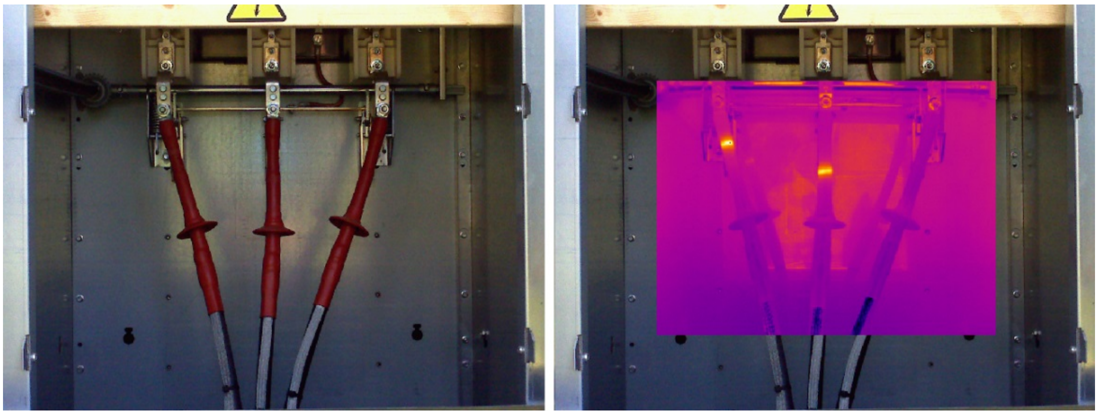


Figure 17: A normal image and a thermal image of a 20 kV indoor termination in operation

The previous case is a good example of how helpful thermal imaging can be in condition monitoring of electrical equipment. The drawback of this technique is that the user may easily misinterpret the seriousness of the local heating seen on an image. Since the phenomena of surface discharges and dry band arcing is not so well known in the field, the real condition of accessories may easily be misjudged, based on this kind of thermal images where local heating is visible.

Figure 18 represents a closer image of a termination where dry band arcing is occurring. A fast look on an image like this gives easily the idea of an extremely hot spot around the termination, which could be caused by a serious problem in the accessory.

The fact is however that the surface of the termination is approximately 22 ˚C and the temperature at the dry band is just slightly above 30 ˚C. A 10 degree temperature increase on the surface of the termination is in no way critical to the accessory's performance. Regardless of this, terminations have still in some cases been replaced rapidly by the network utilities, only based on thermal imaging results similar to this one.

Because of this, it is important to increase the knowledge of surface discharge phenomena for the people working in the field and also clarify the reasons behind dry band formation.

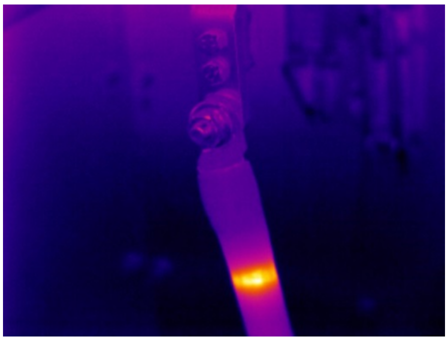


Figure 18: Thermal image of a dry band on a cable termination

2.3 Secondary outdoor substations

Distribution transformers are used to convert the network voltage from medium voltage to low voltage. The voltage level of these transformers is generally 10 or 20 kV on the medium voltage side and 400 V on the low voltage side. Pole mounted outdoor transformers, typically in the range of 50 to 300 kVA, are often used in overhead line networks located in rural areas. These transformers can normally be equipped with disconnectors and surge arresters on the medium voltage side, and fuses or circuit breakers on the low voltage side. [22]

In urban areas where the network is cable-connected, the transformers are often located within commercial or apartment buildings, or inside prefabricated kiosk type single transformer secondary outdoor substations (Figure 19). Various different types and sizes of secondary outdoor substations are available, from bigger looped network models to smaller satellite type substations. [2]

Figure 19: Conventional secondary outdoor substation located in the countryside

The distribution transformer is often part of a looped network in urban areas. The incoming medium voltage feeders are normally equipped with load breaking disconnectors, with the transformer connected to the network loop through a load break switch and a current limiting fuse. [2] The distribution transformers in this kind of substations are generally in the range of 1000 kVA. [22]

Satellite type substations are becoming increasingly popular in situations where the loading of a densely built area increases or in the countryside where the traditional overhead line networks are replaced by underground cables. The structure of a satellite type substation is simple, as the protection is generally implemented at the main infeed substation or at some other intermediate secondary substation. The transformers in the satellite type substations are somewhere in the range of 300 kVA. [22]

The protection of the low voltage side is also implemented at a secondary outdoor substation, with individual low voltage switch fuses providing protection against overloads and faults on the low voltage system. [2]

2.3.1 General structure

The conventional structure of a secondary outdoor substation is mainly air insulated, but also SF6-insulated options are available in modern arrangements. The frame is often made of hot-dip galvanized steel plate with various different outer coatings available. The base of the frame can be made of hot-dip galvanized steel plate or reinforced concrete to give improved resistance against weather and ground frost. An oil basin is included in the base under the transformer to protect the environment against possible oil leaks. The substations are often installed so that the base is partially submerged into the ground, with the foundations under and around the structure made of gravel. [23][24][25]

In the traditional design of a prefabricated secondary outdoor substation, the enclosure is divided into three separate compartments. The first compartment is the medium voltage side which includes the medium voltage feeders, busbars and the switchgear. In case of a design with several feeders this compartment is normally divided further into separate cells, to have the possibility to perform service and maintenance without the need of disconnecting the whole transformer from the network. The second compartment includes the transformer which is generally connected to the medium and low voltage sides by jumper cables. The third compartment is the low voltage side with the low voltage distribution board and all relevant protection.

Regardless of the dimensions, the general setup is to have the transformer positioned between the medium and low voltages compartments, according to Figure 20.

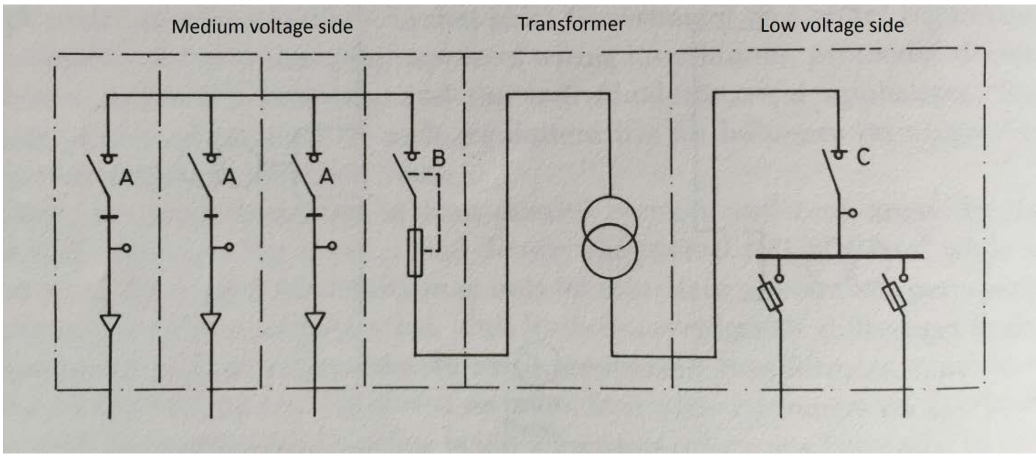


Figure 20: Schematic of a conventional secondary outdoor transformer [2]

The amount of medium voltage cells and the arrangement inside each cell varies between different models. Depending on the outer dimensions of the substation, the terminations can be positioned longitudinally or transversally related to the service hatch of each cell. The incoming underground cables can be brought in to the substation through pipes or directly from the ground.

2.3.2 Typical issues from termination point of view

Various types of medium voltage terminations are used in secondary outdoor substations. Three phase terminations are used on the medium voltage side in the incoming feeder cables and also in both ends of the jumper cable between the transformer and the medium voltage compartment.

One of the main challenges from termination point of view is the environmental conditions inside a substation. A secondary outdoor substation is an unheated enclosure where accessories are installed inside a tight space. The enclosure protects the accessories and equipment inside it from rain and ultra-violet radiation, but it is not tight enough to prevent dust or other small particles from getting in. This result in a situation where the washing effect is prevented and pollution build up gets gradually worse in time (Figure 21).

Figure 21: Severely polluted terminations inside a secondary outdoor substation

As described previously, secondary outdoor substations are generally installed with the base partially submerged. Because of this submerged structure, the terminations inside the medium voltage compartment will often be placed close to the ground or even below ground level, as seen in Figure 22. The submerged structure can result in a significant temperature difference between the upper and lower parts of the enclosure, which increases the risk of condensation in the lower parts of the substation. Because of this temperature difference, the terminations placed closer to the ground will more likely be subjected to a much harder environment than the switchgear and the equipment in the upper parts of the enclosure. [26] The division into compartments affects further on the temperature difference inside the substation, as the heat generated by the transformer does not dry the air inside the medium voltage compartment.

The condensation of water combined with the pollution build up on the surfaces leads to a situation where surface discharges and dry band arcing are an inevitable consequence, especially if the substation is located in an unfavorable area with heavy pollutants, and also if wrong type of accessories are used.

Figure 22: Partially submerged structure with terminations below ground level

Regardless of the pollution build up and condensation of water, indoor terminations have been widely used in secondary outdoor substations. Reasons for this in addition to price could be possible lack of knowledge and the limited space inside the substations. Indoor terminations are generally shorter and have less rain sheds or no rain sheds at all, which makes them more convenient to install inside a tight enclosure.

The limited space inside the cramped cells is also a challenge for the installer, at least if the accessory needs to be installed inside the cell. Especially heat shrink terminations can be problematic to install properly, since the heat should be applied uniformly from all sides of the accessory. Even if the installation is done outside of the cell the termination should be reheated after bending it into its final position. Problems with the shrinking can be seen afterwards as partially loose rain sheds or uneven surface on the termination.

Issues related to the limited space inside the substation can sometimes be seen when parallel or different phases are touching each other, termination surfaces are in contact with ground or when the terminations are installed too close to live parts of auxiliary equipment, as seen in Figure 23. The electrical field strength on the surface of the termination becomes biased by these kinds of flaws and surface discharges can occur.

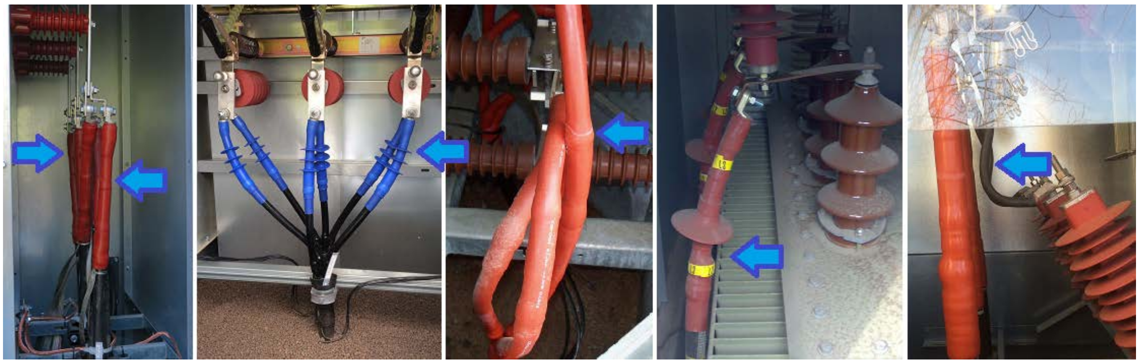


Figure 23: Problematic installations from real life

3 Fault data from network utilities

The occurrence of surface discharges in real operating conditions has been studied by inspecting aged medium voltage terminations operating inside secondary outdoor substations. The inspections have been done within the past years in co-operation with different Finnish subcontractors and network utilities. The aim of the inspections was to look for traces of surface discharges in aged terminations and thereby to be able to prevent possible damage to the accessories in advance.

Four separate inspection cases were done between the years 2011 and 2014. The inspections included a visual inspection, photographing and in some cases also thermal imaging of the terminations. The inspectors recorded information and details of each inspected substation, including location, installation date, substation model, termination type and other relevant information.

A total number of 646 secondary outdoor substations were inspected during these four cases. The inspections include data of approximately 1700 three-core cable terminations. Since all these terminations were inspected phase by phase the total number of inspected single-core medium voltage terminations was above 5100. Processing of all this data takes quite a lot time and therefore one of the main goals of this work was to analyze the data and convert it into a suitable format, so that it can be used for statistical study of the surface discharge phenomena.

All traces of surface discharges are marked as “Faults” in the Tables, regardless of the extent of the discharge traces or the condition of the termination. This is a bit misleading in most cases, since the terminations are not damage in any way. The method used for identifying the discharge activity has not been classified in the results. Many of the terminations only have faint marks of dry band arcing somewhere along the surface. Regardless of these discharge traces, the majority of these terminations could operate for years or even decades without any further problems.

3.1 Inspection case 1

The first inspection case was performed during late spring 2011. The aim was to collect information of the terminations used in the jumper cables which connect the transformer to the medium voltage compartment. The inspection included data from 99 secondary outdoor transformers and 197 three-core terminations. One of the terminations is missing from the results, because the cell was not accessible during the inspection.

Substation model

Three different substation models were included in this inspection (S1 – S3). Discharge traces on the terminations were found in nine substations, which equal 9.1 % of all inspected secondary outdoor substations. All these nine substations were of the same S1 model. The division of substations by model is presented in Table 4.

Table 4: Secondary outdoor substations (Case 1)

Substation	Amount	Faults	Fault %
S1	79	9	11.4 %
S2	19	0	-
S3	1	0	-
Total amount	*99*	*9*	*9.1 %*

One interesting finding was that all terminations that had traces of surface discharges were located on the busbar side of the jumper cable, i.e. inside the medium voltage compartment.

Substation S1 was the only one where discharges were noticed and therefore it is also the only one that will be analyzed more closely in this section. The medium voltage compartment in substation S1 contains several medium voltage cells. The cells are built up so that the terminations are lined up in a perpendicular row inside the cells. This means that the first phase (L1) is located closes to the door, the third phase (L3) closest to the inner wall in the middle of the substation and the second phase (L2) between the two other phases. Because of this perpendicular phase alignment, the discharge division between different phases was also analyzed. The division of surface discharges per phase is represented in Table 5.

Table 5: Substation S1 faults divided by phase (Case 1)

Phase	Amount	Faults	Fault %
L1	79	7	8.9 %
L2	79	7	8.9 %
L3	79	1	1.3 %
Total amount	*237*	*15*	*6.3 %*

Phases L1 and L2 had traces of surface discharges in 7 out of 79 inspected terminations (8.9 %), whereas phase L3 only had traces on one termination (1.3 %). The number of samples is low but this division still indicates that the phases located closer to the door could have a higher probability for surface discharges in this kind of a structure. A reason for this kind of division could be caused by airborne pollution originating from outside the substation. If this is the case, the phases located closer to the door will have a higher pollution buildup on the termination surface and therefore also the probability for surface discharges increases.

Termination types

Another approach in analyzing the inspection results is to look at the termination types used inside these substations. Six different types of medium voltage terminations were used inside these 99 inspected secondary outdoor substations. Since the terminations were examined individually, the total number of inspected single-core terminations was 591.

The division of terminations according to indoor or outdoor use and heat shrink or cold shrink technology is shown in Table 6. In Table 7 the terminations are divided individually by type.

Table 6: Inspected terminations (Case 1)

Amount of terminations				Faults	
Termination type	All	Transformer	Busbar	Faults (busbar)	Fault % (busbar)
Indoor	564	294	270	15	5.6 %
Outdoor	27	0	27	0	-
Heat shrink	570	282	288	15	5.2 %
Cold shrink	21	12	9	0	-

Table 7: Terminations divided by type (Case 1)

Termination	All	Transformer	Busbar	Faults (busbar)	Fault % (busbar)
T1	487	254	233	15	6.4 %
T2	21	0	21	0	-
T3	56	28	28	0	-
T4	6	0	6	0	-
T5	9	6	3	0	-
T6	12	6	6	0	-
Total amount	*591*	*294*	*297*	*15*	*5.1 %*

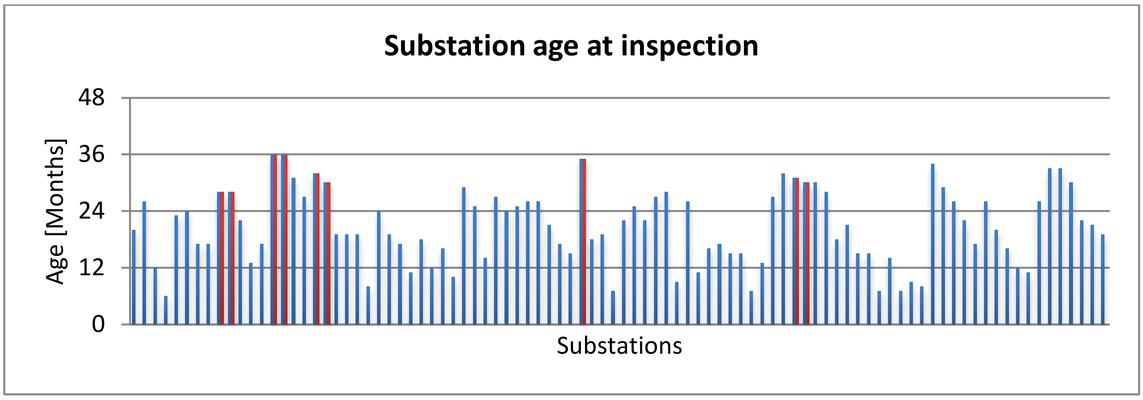
Terminations T1 and T3 are both heat shrink indoor terminations. T2 and T4 are heat shrink outdoor terminations and T5 and T6 are cold shrink indoor terminations. The results in Table 6 clearly indicate that the majority of terminations are heat shrink indoor terminations. Only less than 5 % of all inspected terminations are outdoor terminations regardless of fact that the operating conditions inside a secondary outdoor substation can be harsh.

Only 15 of all the 591 inspected terminations had traces of surface discharges. All these terminations were of type T1. Termination T1 was also clearly the most used termination type inside these substations. The amount of faults and the fault percentages are only presented from the busbar side of the jumper cable, since no faults were found on the terminations on the transformer side.

Substation age

One more approach to analyze the results is to look at the age of the inspected substations. 92 of all the 99 inspected substations had the installation date available. The age of these substations was between 6 and 36 months with an average age of 21 months.

The age of these 92 substations is presented by the blue bars in Graph 1. The red bars are used to visualize the substations where terminations with discharges traces were found.



Graph 1: Substation age (Case 1)

The substations with traces of discharges on the terminations were between 28 and 36 months old with and average age of 32 months.

These results also strengthen the assumption that external pollution plays a key role in the occurrence of surface discharges. This is because discharges traces were only found on terminations in some of the older substations. Based on this, it can be assumed that it takes time before enough conducting particles build up on the termination surface and the discharge occurrence starts.

3.2 Inspection case 2

The second inspection case was performed during spring 2012, one year after the first case. This inspection was performed in the same way as the first one, mainly focusing on the jumper cables between the transformer and the medium voltage compartment. The inspection contains data from 285 secondary outdoor transformers and 565 three-core terminations used in the jumper cables. Data of some terminations is missing, because the cells have not been accessible during the inspection.

In addition to the jumper cable terminations, also 14 network side terminations were inspected. These 14 terminations will not be taken into account in the results of this inspection case, since the number of samples was low and the focus of this inspection was mainly in the jumper cable terminations.

Another inspection was performed for 68 of these 285 secondary outdoor substations, approximately one year after this inspection. The results of this re-inspection will be discussed in the next section as a separate inspection case.

Substation model

Three different secondary outdoor substation models were included in the second inspection case (S1, S2 and S4). Traces of surface discharges were found on the terminations in 84 substations out of 285 (29.5 %). Substations S1 and S2 both had traces of surface discharges on the jumper cable terminations. The division of substations by model can be seen in Table 8.

Table 8: Secondary outdoor substations (Case 2)

Substation	Amount	Faults	Fault %
S1	204	80	39.2 %
S2	80	4	5.0 %
S4	1	0	-
Total amount	*285*	*84*	*29.5 %*

The majority of all terminations with surface discharge traces were located on the busbar side of the jumper cable.

Two of the inspected substations also had traces of discharges on the transformer side terminations. Both of these substations were located in exactly the same region in close vicinity to the sea and traces of discharges were found on all three transformer side terminations in both substations. One of the substations was of model S1 and the other one of model S2. Indoor terminations were used in both substations regardless of the vicinity to the sea.

Table 9 represents the division of surface discharges between different busbar side phases in substation S1. The same division for substation S2 is represented in Table 10.

Table 9: Substation S1 faults divided by phase (Case 2)

Phase	Amount	Faults	Fault %
L1	204	68	33.3 %
L2	204	56	27.5 %
L3	204	53	26.0 %
Total amount	*612*	*177*	*28.9 %*

Table 10: Substation S2 faults divided by phase (Case 2)

Phase	Amount	Faults	Fault %
L1	80	3	3.8 %
L2	80	3	3.8 %
L3	80	2	2.5 %
Total amount	*240*	*8*	*3.3 %*

The discharge distribution between the phases shows a similar trend for substations S1 as what was seen in the previous inspection case. The occurrence of discharges is clearly higher on phase L1 (33.3 %) closest to the door, when compared to the discharge occurrence of phases L2 (27.5 %) and L3 (26.0 %).

The structure of substation S2 is smaller than S1 and the phases are positioned in a row next to each other. The distance from each phase to the outside of the substation is more uniform in this kind of structure. The identification of phases has in this case been done from left to right (L1 – L2 – L3). Phases L1 and L2 both had 3 terminations with discharge traces, whereas phase L3 had traces on 2 terminations. With this small variance between the phases, no clear trend can be seen in the discharge distribution for substation S2.

Termination types

Seven different termination types were used in these 285 inspected secondary outdoor substations. The total number of inspected single-core terminations on the jumper cables was 1695 and the division of terminations based on their operating environment, installation technology and type can be seen in Table 11and Table 12.

Table 11: Inspected terminations (Case 2)

Amount of terminations				Faults	
Termination type	All	Transformer	Busbar	Faults (busbar)	Fault % (busbar)
Indoor	1308	546	762	183	24.0 %
Outdoor	93	15	78	2	2.6 %
Heat shrink	1316	526	790	185	23.4 %
Cold shrink	85	35	50	0	-

Table 12: Terminations divided by type (Case 2)

Termination	All	Transformer	Busbar	Faults (busbar)	Fault % (busbar)
T1	1120	474	646	181	28.0 %
T2	81	9	72	2	2.8 %
T3	112	43	69	2	2.9 %
T4	3	0	3	0	-
T5	76	29	47	0	-
T7	9	6	3	0	-
T8	294	294	0	-	-
Total amount	1695	855	840	185	22.0 %

Terminations T1 – T5 are the same as in the first inspection case. T7 is a cold shrink outdoor termination and T8 a screened termination that is only used on the transformer side in these substations. T8 is excluded from Table 11 because of its screened design.

With the screened terminations excluded from the results, the ratio between indoor and outdoor terminations is similar as in the first inspection case. Only less than 7 % of all inspected terminations are intended for outdoor use.

Traces of surface discharges were found on 191 of all the 1695 inspected terminations. Six of the terminations with discharge traces were located on the transformer side of the jumper cable in the two substations located in close vicinity to the sea. These terminations are not shown in the tables as they represent only 0.7 % of all transformer side terminations and were already discussed separately.

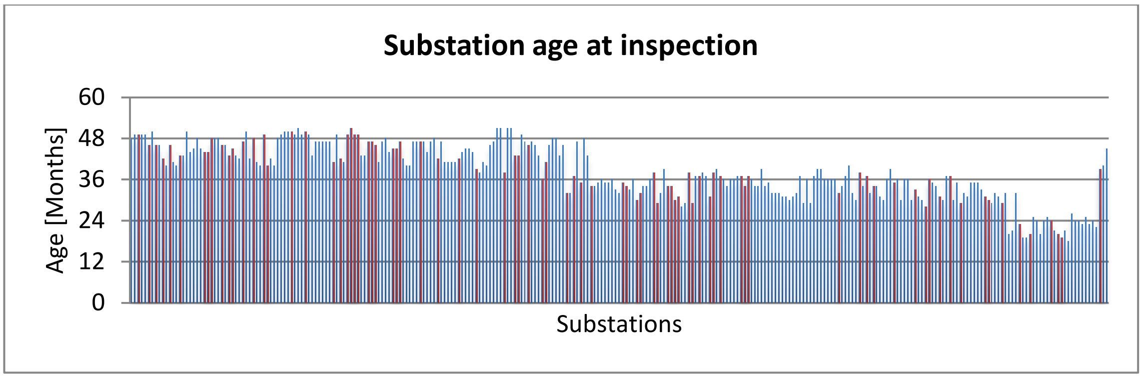
The majority of all surface discharge traces were found in termination T1, which was also the most used termination type in these substations. Terminations T2 and T3 also had traces of discharges on two individual terminations per type, but the fault percentage for these two is significantly lower than what it is for termination T1.

Substation age

The installation date was available for 281 of all 285 inspected substations. The age of these substations was between 18 and 51 months with an average age of approximately 38 months. The age of the substations is presented in Graph 2.

As in the previous case, each blue bar represents an inspected substation and the red bars are used to visualize the substations with traces of discharges.

The substations that had traces of discharges in the terminations were between 19 and 51 months old with and average age slightly above 38 months.



Graph 2: Substation age (Case 2)

3.3 Inspection case 3

A re-inspection was done for 68 of the previously inspected 285 secondary outdoor substations. The inspection was done during spring 2013, approximately one year after the original inspection for the same substations.

The two previous inspections had proved that surface discharges were not very commonly found on the transformer side, so the focus of this inspection was on the terminations located inside the medium voltage compartment. The inspection contains data from 68 substations and 181 three-core terminations. The data is collected from both jumper cable terminations and network cable terminations in the medium voltage compartment.

It is unclear how these 68 substations were selected for this inspection, but they are quite evenly scattered around different regions of the original inspection. 26 (38.2 %) of these 68 substations had discharge traces on the terminations already in the previous inspection. If no maintenance actions were performed between these two inspections, the fault percentage for the substations can only be equal or higher than this when the network cable terminations are included.

Substation model

Substation models S1 and S2 were included in this inspection. Exactly half of the inspected substations had traces of surface discharges on at least one of the terminations. The increased percentage can partly be explained by the bigger amount of inspected terminations inside one substation, but also the time between these inspections could give rise to new surface discharges on terminations that previously were OK. The division of substations by model is shown in Table 13.

Table 13: Secondary outdoor substations (Case 3)

Substation	Amount	Faults	Fault %
S1	52	28	53.8 %
S2	16	6	37.5 %
Total amount	*68*	*34*	*50.0 %*

The majority of the terminations with discharge traces were found in substation S1. A notable difference to the previous inspection cases was the relatively high percentage of S2 substations that also had traces of discharges on the terminations. The higher percentage could be partially explained by the small amount of inspected units, but it also seems like the network cable terminations have a higher probability for surface discharges in this substation model. The network cable terminations are located much closer to the ground in this structure, which means that the operating conditions are also rougher. The division of surface discharges between different phases in both substation types can be seen in Table 14 and Table 15.

Table 14: Substation S1 faults divided by phase (Case 3)

Phase	Amount	Faults	Fault %
L1	160	45	28.1 %
L2	160	44	27.5 %
L3	160	40	25.0 %
Total amount	*480*	*129*	*26.9 %*

Table 15: Substation S2 faults divided by phase (Case 3)

Phase	Amount	Faults	Fault %
L1	21	6	28.6 %
L2	21	8	38.1 %
L3	21	6	28.6 %
Total amount	*63*	20	31.7 %

The discharge distribution between the phases is small for substations S1, but the same trend can still be seen here as in the previous cases. Phases L1 and L2 which are located closer to the door have a higher amount of discharge traces on them than phase L3 further inside the substation.

The results in Table 15 clearly indicate that phase L2 has a higher amount of discharge traces in substation S2. The previous case did not show a similar trend and the amounts here are so small that this is expected to be more random than an actual trend in the discharge distribution.

Termination types

Six different termination types were used in these 68 re-inspected secondary outdoor substations. The total number of inspected single-core terminations was 543 and the division of terminations based on their operating environment, installation technology and type can be seen in Table 16 and Table 17.

Table 16: Inspected terminations (Case 3)

Termination type	Amount	Faults (busbar)	Fault % (busbar)
Indoor	492	147	29.9 %
Outdoor	51	2	3.9 %
Heat shrink	537	149	27.7 %
Cold shrink	6	0	-

Table 17: Terminations divided by type (Case 3)

Termination	Amount	Faults (busbar)	Fault % (busbar)
T1	287	146	50.9 %
T2	30	2	6.7 %
T3	202	1	0.5 %
T4	18	0	-
T5	3	0	-
T7	3	0	-
Total amount	*543*	*149*	*27.4 %*

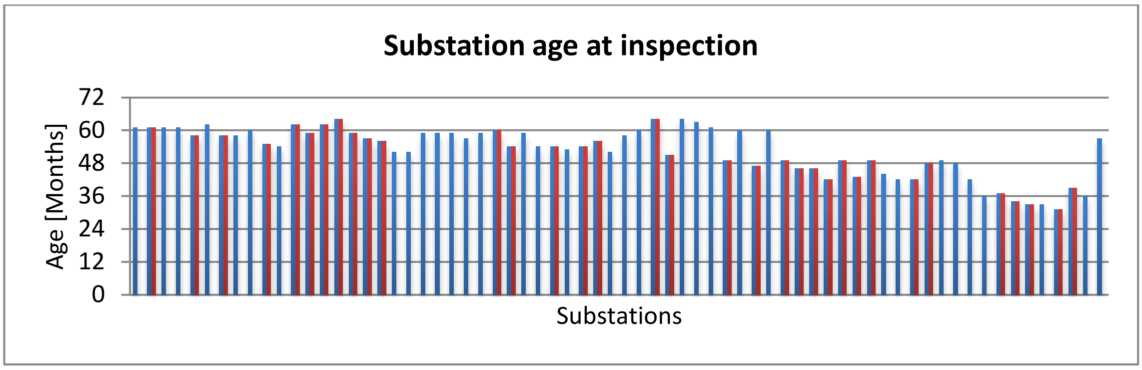
All terminations used in these re-inspected substations are of the same types what has been described in the previous inspection cases. With the network cable terminations included in this inspection, the ratio between indoor and outdoor terminations is still quite similar as in the previous two inspection cases. Less than 10 % of all the 543 inspected terminations are designed to be used in an outdoor environment.

The distribution of surface discharge traces between different termination types was similar as in the previous inspection cases. The majority of all discharge traces were found in termination T1. More than half of all T1 terminations had some form of discharge traces visible. Also a few individual T2 and T3 terminations had traces of surface discharges.

Substation age

All of these 68 re-inspected substations had the installation date available. The age of the substations was between 31 and 64 months during the inspection, with and average age around 53 months.

Graph 3 represents the age of all the inspected substations and the substations where terminations with surface discharge traces were found. The substations that had traces of discharges in the terminations were between 31 and 64 months old with an average age of approximately 51 months.



Graph 3: Substation age (Case 3)

3.4 Inspection case 4

The fourth inspection case was performed during early winter 2014. The aim of this inspection was similar as in the previous cases, to inspect a huge amount of substations and check the condition of the cable terminations in them. Inspections were performed for 262 different secondary outdoor substations, including data of 765 three-core medium voltage terminations. Jumper cable terminations and network cable terminations were inspected in this case.

The inspection focused mainly on the substations where abnormalities were found by the inspectors. Because of this, the data regarding all the other substations is not as comprehensive as it has been in the previous inspection cases. Also no pictures were taken in the substations where no abnormalities were found. Since the pictures are missing from the majority of substations, the type of all terminations can't be accurately defined afterwards.

Substation model

The fourth inspection case differs from the previous cases especially regarding the amount of different substation model that were inspected. The inspection included 20 different substation models from various manufacturers.

Substations S1, S2 and S4 are the same ones as in the previous inspection cases. A clear majority of all inspected substations were in this case also of model S1 (48.5 %). The new substation models in this inspection (S5 – S21) included a wide variety of different sizes and structures. Because of the huge amount of different models, the structure of each one will not be analyzed closely.

The amount of substations and amount of units with surface discharges in the terminations is shown in Table 18.

Table 18: Secondary outdoor substations (Case 4)

Substation type	Amount	Faults	Fault %
S1	127	30	23.6 %
S2	18	1	5.6 %
S4	1	0	-
S5	8	0	-
S6	3	0	-
S7	1	0	-
S8	1	0	-
S9	29	0	-
S10	8	0	-
S11	40	2	5.0 %
S12	1	0	-
S13	7	0	-
S14	6	0	-
S15	1	0	-
S16	2	0	-
S17	4	1	25.0 %
S18	2	0	-
S19	1	0	-
S20	1	0	-
S21	1	0	-
Total amount	*262*	*34*	*13.0 %*

The majority of terminations with discharge traces were found in substations model S1. Substations S2, S11 and S17 also had traces of surface discharges on some individual units. Substation S17 has the highest percentage of inspected units with discharge traces (25 %), but the number of inspected substations of this model is too low to really have a reliable value.

The discharge distribution between the phases in substation S1 was analyzed because a clear trend was seen in the previous inspections. This distribution is presented in Table 19. The discharge distribution was not analyzed for any of the other substations models because the amount of faults was too low.

Table 19: Substation S1 faults divided by phase (Case 4)

Phase	Amount	Faults	Fault %
L1	127	40	31.5 %
L2	127	31	24.4 %
L3	127	32	25.2 %
Total amount	381	103	27.0 %

A clearly higher amount of discharge traces were found in phase L1 than what was found in phases L2 and L3. Also these results affirm the assumption that the phases locate closer to the outside have a higher probability for surface discharges in this substations model.

Termination type

The total number of inspected single-core terminations was 2295. The exact type of each individual termination was not precisely recorded and could not be defined afterwards without the photos from all substations. The data was however sufficient enough to distinguish the difference between indoor and outdoor terminations in most cases and also if the terminations were made using heat shrink or cold shrink technology.

An estimation of the used termination types and the discharge traces found in them are represented in Table 20. Exactly all inspected terminations are not included in this table, since they were marked as “Unknown” by the inspectors. The number of outdoor terminations might be slightly higher than what is marked in the tables, because the lack of photos for verification. These results are still well in line with the results obtained from the previous inspections cases and are therefore assumed to represent a somewhat correct estimation of the real situation inside these substations.

Table 20: Inspected terminations (Case 4)

Type	All	Transformer	Busbar	Transformer	Busbar	Busbar fault %
Indoor	2124	669	1455	4	101	6,9 %
Outdoor	135	30	105	0	6	5,7 %
Heat shrink	2031	585	1446	4	107	7,4 %
Cold shrink	228	114	114	0	0	-

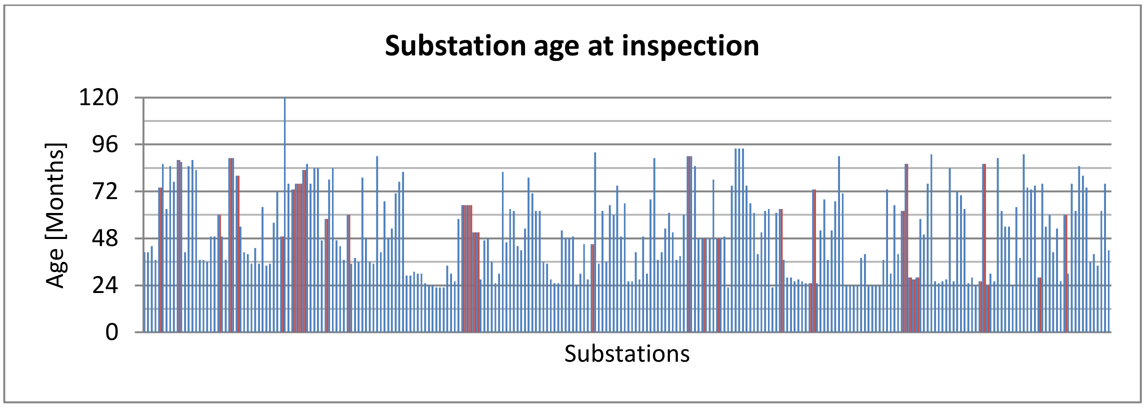
Based on these estimated results, the ratio between indoor and outdoor terminations was similar as in the previous inspection cases. According to these numbers, only about 6 % of the terminations used in these substations are designed for outdoor use. The number of outdoor terminations could be slightly higher, but this does not affect the ratio significantly.

Substation age

All of the 262 inspected substations had the installation dates available. The majority of the inspected substations were between 23 and 94 months old with one single substation at an age of 216 months. By removing this one clearly older substation from the results, the average age of the substations becomes slightly below 52 months.

Graph 4 represents the age of all the inspected substations and the substations where terminations with surface discharge traces were found.

The age of the substations where surface traces were found was between 24 and 90 months with and average value of 59 months.



Graph 4: Substation age (Case 4)

3.5 Assessment of inspection results

The results from each inspection case were presented and discussed separately in the previous sections. In order to get a better overview of the general situation on the field, the results from all four inspection cases are analyzed here as a whole. As already mentioned in the beginning of the chapter, the inspections include data from 646 secondary outdoor substations from which 68 were inspected twice. The division of substations per inspection case is presented in Table 21.

Table 21: Inspected substations

Inspected substations	
Case 1	99
Case 2	285
Case 3	(68)
Case 4	262
Total amount	*646*

The exact cause and severity of each discharge trace will of course not be analyzed, but the aim is to clarify the reasons that could lead to surface discharges on the terminations to improve the performance of future assemblies.

The results of the individual inspection cases showed clear similarities in the conditions and matters affecting the occurrence of discharges. The discharge occurrence on the terminations seems to mainly be related to:

- Termination type
- Substation model or structure
- Age of the substation (Termination age)

It is clear that the termination itself plays a key role in the occurrence of discharges on its surface. As the terminations are used inside a secondary outdoor substation, the construction of this enclosure also has some effect on the discharge occurrence. The discharge phenomena takes time to build up and therefore also the ageing time plays an important role in the occurrence of surface discharges on the terminations.

The effect of these points will be analyzed individually in the following sections.

3.5.1 Termination type

As expected, the termination itself is one of the main factors affecting the performance of the accessories operating in outdoor environments.

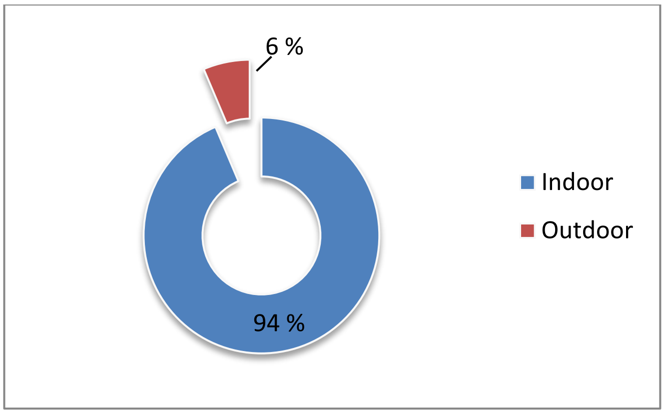
The total number of inspected single-core terminations was slightly above 5100, but roughly 300 of these were excluded from the following results because of screened designs or an unknown termination type. The division of terminations by inspection case can be seen in Table 22. As previously mentioned, the results for inspection case 4 are not exact because of missing data, but they represent a good estimation of the situation in these inspected substations.

Table 22: Inspected terminations

Termination type	Case 1	Case 2	Case 3	Case 4	All	Faults	Fault %
Indoor	564	1308	492	2124	4488	456	10.2 %
Outdoor	27	93	51	135	306	10	3.3 %
Heat shrink	570	1316	537	2031	4454	466	10.5 %
Cold shrink	21	85	6	228	340	0	-
Total amount	*591*	*1401*	*543*	*2259*	*4794*	*466*	*9.7 %*

A surprisingly high amount of all inspected terminations are indoor terminations. Indoor terminations have shorter creepage distances and it is generally not advisable to use them in rough operating environment where moisture and pollutants are present. The performance difference between indoor and outdoor terminations can clearly be seen from the fault percentages in Table 22.

The division of indoor and outdoor terminations in the inspected substations is presented in Graph 5.



Graph 5: Division of terminations

Another surprising point was that none of the inspected cold shrink terminations had any traces of surface discharges noticed. What makes this interesting is the fact that the majority of all cold shrink terminations were indoor terminations with a relatively short creepage distance.

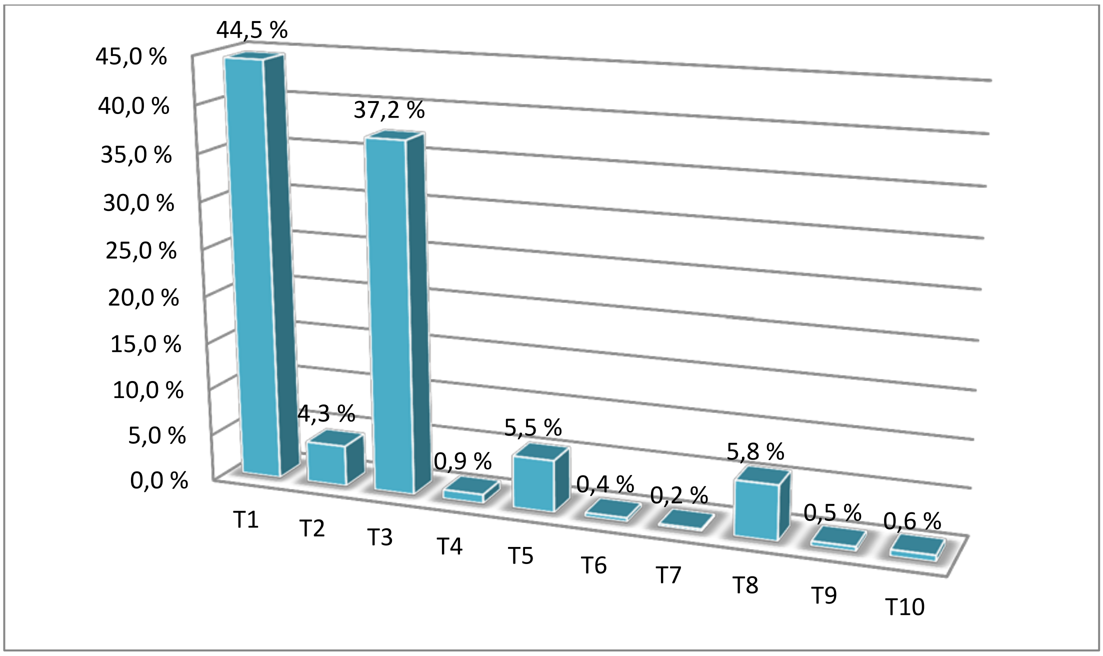
Cold shrink terminations are manufactured from silicon rubber that maintains better its hydrophobic properties than the polymers used in the heat shrink terminations. [27]

As mentioned in the theory part, hydrophobic materials like silicon rubber has already been successfully used in outdoor insulators located in polluted areas. Based on these results, it seems like the hydrophobic surface and the recovery of this hydrophobicity plays also a key role in the performance of the terminations used inside outdoor enclosures where the washing effect of rain is removed.

Significant performance differences can be seen between different terminations when the results are analyzed based on individual terminations types. The following ten terminations types were included in the inspections:

- T1: Heat shrink indoor termination
- T2: Heat shrink outdoor termination
- T3: Heat shrink indoor termination
- T4: Heat shrink outdoor termination
- T5: Cold shrink indoor termination
- T6: Cold shrink indoor termination
- T7: Cold shrink outdoor termination
- T8: Screened termination
- T9: Cold shrink outdoor termination
- T10: Unknown termination

An estimation of the division of all the 5124 inspected single-core termination types is presented in Graph 6. The exact numbers are not presented, since the photos were not available for all substations in inspections case 4 and the results are assumed to contain small inaccuracy because of this.



Graph 6: Division of terminations by type

Clear differences are seen in the performance of different termination types. Surface discharges and discharge traces were found in termination types T1, T2 and T3. All these terminations are commonly used in the cable network and they fulfill the standard requirements for their type of accessories.

Regardless of the type tested designs, differences are especially seen in the performance of the heat shrink indoor terminations when they are subjected to the harsh environment inside a secondary outdoor substation. The difference is significant, as more than 19 % of all inspected T1 terminations had traces of discharges, whereas the same number for T3 terminations is less than 0.5 %. This difference demonstrates well how different models or revisions of the same accessory type can offer completely different performance in an unfavorable environment.

About 4.5 % of all inspected T2 terminations had traces of surface discharges on them. The discharge traces on the outdoor terminations also indicate that a longer creepage distance alone is not sufficient to provide flawless operation in all environments with varying contamination levels.

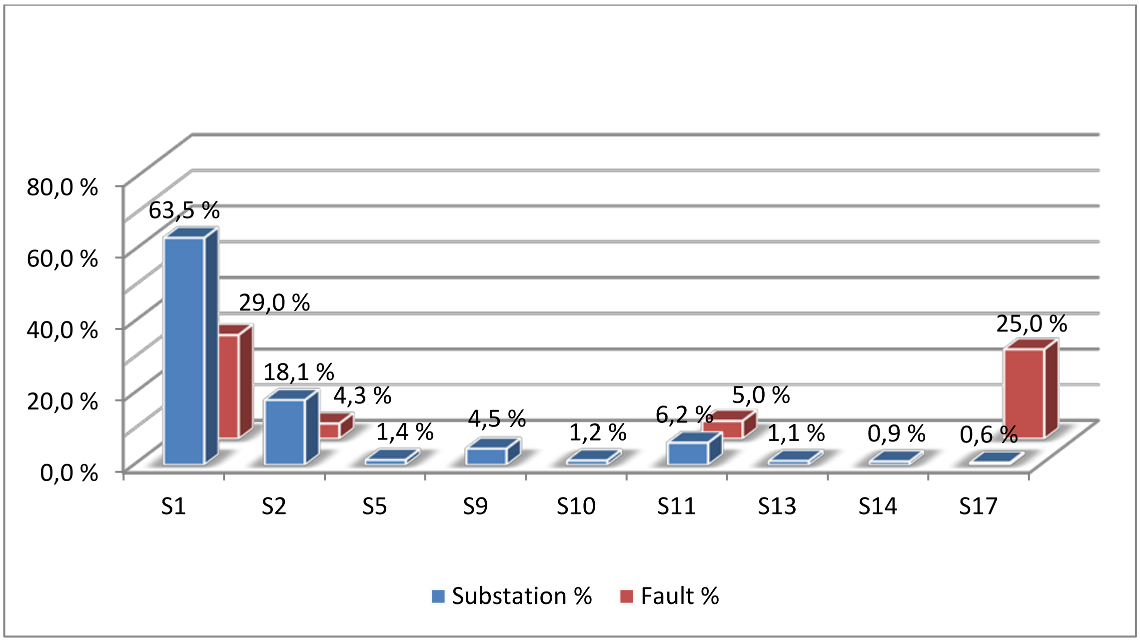
3.5.2 Substation model

Also the model of the substation seems to have some effect on the occurrence of surface discharges in the cable terminations. Different substation models vary in space and shape, which can also affect the discharge occurrence on the accessories used inside the enclosure. As moisture and pollution are some of the main components needed for the surface discharge phenomena, the influence of the enclosure itself is quite evident.

A clear majority of all discharge traces were found on the terminations located inside the medium voltage compartment, whereas the transformer side terminations were mainly OK. The performance difference on the same terminations clearly indicates that the conditions inside these two compartments are different. The heat generated by the transformer is expected to be one of the main reasons behind this difference, as the humidity inside the transformer side stays lower.

From the 646 inspected substations, 127 (9 %) had traces of surface discharges on the terminations. More than 80 % of all inspected substations were of model S1 or S2, but the inspections still included 21 different models. Discharge traces on the terminations were only found in four of these substation models.

The division of substations by model is presented in Graph 7. The results of inspection case 3 are excluded from this graph since the same substations were re-inspected. The blue bars represent the percentage of each substation model compared to the total number of inspected substations and the red bars indicate the fault percentage for each model. Only the substations where faults were noticed or models with more than four inspected units are presented in the graph.



Graph 7: Division of substations by model

A clear majority of all surface discharge traces were found on the terminations in substation S1. The fault percentage for substation S17 is not assumed to be very accurate because the number of inspected units was only four and traces of surface discharges were found in one of these.

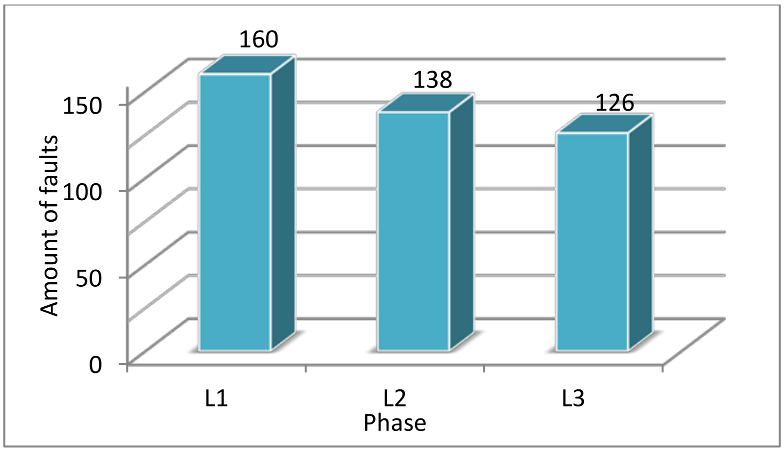
These results support the assumption that the substation model could also affect the performance of the terminations used inside them.

Phase position inside the substation

The phase position inside a substation can also affect the discharge occurrence on individual terminations. This behavior is not an actual reason for the discharges but a feature noticed in certain substation models.

The division of discharges per phase was analyzed more closely for substation S1, because the phases are lined in a perpendicular row inside its medium voltage cells. The result of such alignment is that the distance to the outside of the substation is different for each phase inside the cell. This varying distance results in an uneven discharge distribution between the different phases. The situation is not clearly seen in every substation since workmanship and other factors can also affect the occurrence of surface discharges. Regardless of this, a clear trend is seen in the results when the results of all four inspection cases are combined.

The total amount of discharge traces per phase from all four inspection cases is presented in Graph 8. The phases are marked L1 – L2 – L3, starting from the outside and heading inwards, toward the center of the substation.



Graph 8: Division of faults per phase (Substation S1)

By studying the amount of discharge traces in this way, the source for the conducting pollutants can be clarified. A clear trend can be seen in the discharge distribution between the phases, as the discharge occurrence increases towards the outside of the substation.

Moisture and conducting particles are the two key ingredients for the surface discharge phenomena, so the assumption is that this kind of discharge distribution is mainly caused by external pollutants. As the substation is not completely airtight, airborne particles can easily get in from the springs and gaps of the enclosure. If this assumption is correct, the phases located closer to the outer edge of the substation are more exposed to environmental contaminants and therefore also have a higher amount of discharge traces on them.

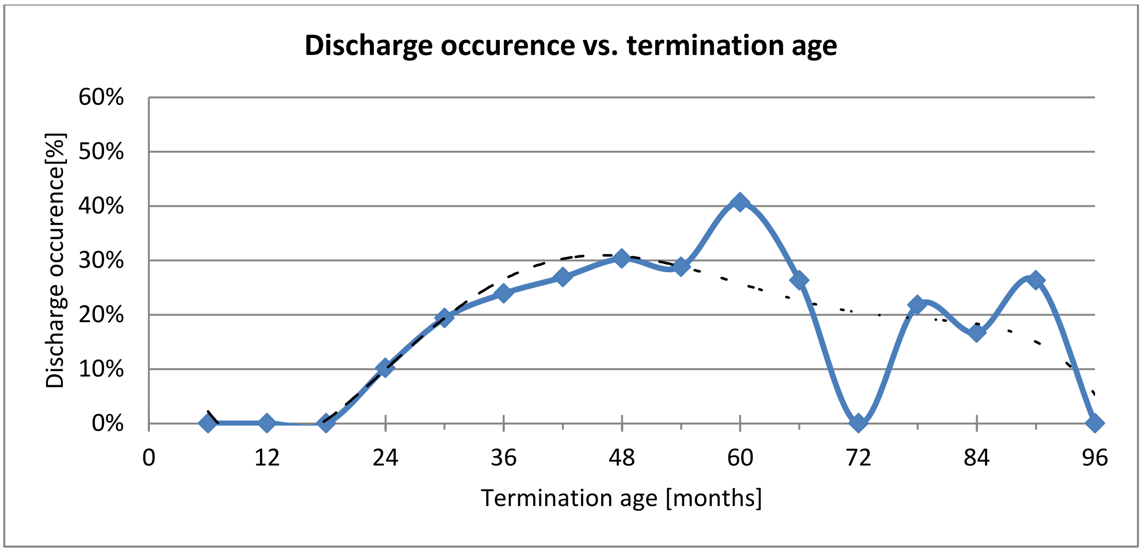
So, based on these result the environmental conditions outside the substation also have an impact on the performance of the terminations used inside them. This means that the fault percentages will also be higher in the substations located in areas with rougher environmental contaminants.

3.5.3 Termination age

As the majority of all substations had the installation date available, the occurrence of discharges could also be analyzed based on the substation age.

All substations with an age between 0 – 96 months were divided into groups with six month intervals (0 – 6, 7 – 12, 13 – 18, etc.) according to their age. The amount of substations with discharges or discharge traces on the terminations in each group was calculated and compared to the number of inspected substations in that group. This calculated discharge occurrence represents an estimation of how many of the inspected substations at a certain age would have traces of surface discharges visible in the terminations, if the substations would be inspected with six month intervals. The calculated discharge occurrence is presented Graph 9.

The presented results are of course not absolutely correct since no records were available of any possible maintenance work done for the substations or to the terminations during their lifetime. The age of these substations is relatively low so the majority of them have probably not yet been part of any scheduled maintenance. Because of this the results are expected to give a quite good indication of what the situation in the field actually looks like.



Graph 9: Discharge occurrence vs. termination age

None of the inspected substations with an age below 18 months had any traces of discharges. Thereafter the discharge occurrence increases gradually from 18 to 48 months. In substations at an age of around four years, the discharge occurrence in the terminations is approximately 30 %. From 48 to 96 months the trend for the discharge occurrence becomes slightly decreasing, but the deviation between these results is also very high. According to these results, there could be a 20 – 40 % chance to find some traces of surface discharges on the terminations in a substation at an age between four and eight years.

The data indicates well the general behavior of the surface discharge phenomena. As we can see from these results, surface discharges are not occurring at all in new and clean installations. When time goes by and a layer of conducting particles builds up on the surface of the terminations, the discharges slowly start to occur. The varying environmental conditions lead to a gradually increasing discharge occurrence in substations located in different areas. In cases where the operating environment is not too harsh for the accessory, discharges should never occur. Because of this, the increasing discharge occurrence presented in the graph stops at a certain value. The reason for the decreasing trend in the discharge occurrence of the older terminations is unknown but it could be related to scheduled maintenance. Other possible reasons for the better performance of the older installations could also be changes in termination and substation designs or material changes within the recent years. Also changes in general building practices for the substation foundations could affect the performance of the terminations, as moisture and humidity play a key role in the surface discharge phenomena.

4 Laboratory tests

Different laboratory tests were done to study the surface discharge phenomena and the performance difference between various medium voltage terminations.

The tracking resistance of different surface materials was studied in the inclined plane test (Tracking test). Different terminations were also compared in a salt fog test where several products were tested simultaneously. The lifetime of the accessories was studied by increasing the test time of the salt fog test further above the type test requirement.

Experimental high voltage tests were performed in a fog chamber to study the discharge phenomena further. A small fog chamber was built for these experimental tests.

4.1 Tracking test

Performance of different material samples and surface coatings was studied in the inclined plane test (Tracking test). The resistance to tracking and erosion was compared by using liquid contaminant and inclined plane specimens. The test was performed in a tests chamber specially built for this purpose (Figure 24).

Figure 24: Test chamber for the inclined plane test

The test procedure was done according to IEC60587:2007, Method 2. Five samples of the same material type were tested simultaneously. The samples were installed inclined in a rack with electrodes 50 mm apart from each other and conducting liquid was fed from the top so that it flowed uniformly along the surface of each sample. The voltage was increased stepwise every 60 minutes with 0.25 kV steps, starting from 2.75 kV. The leakage current was measured for each sample. The test was continued until the leakage current through a sample exceeded 60 mA or until a hole had eroded through the material or it ignited. Examples of already tested material samples can be seen in Figure 25.

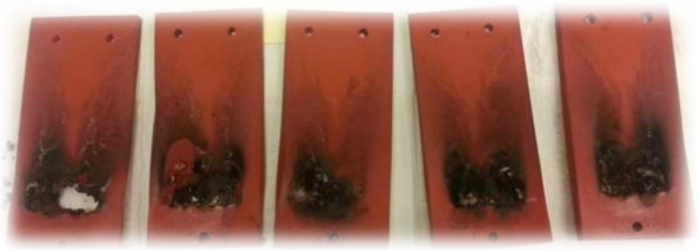
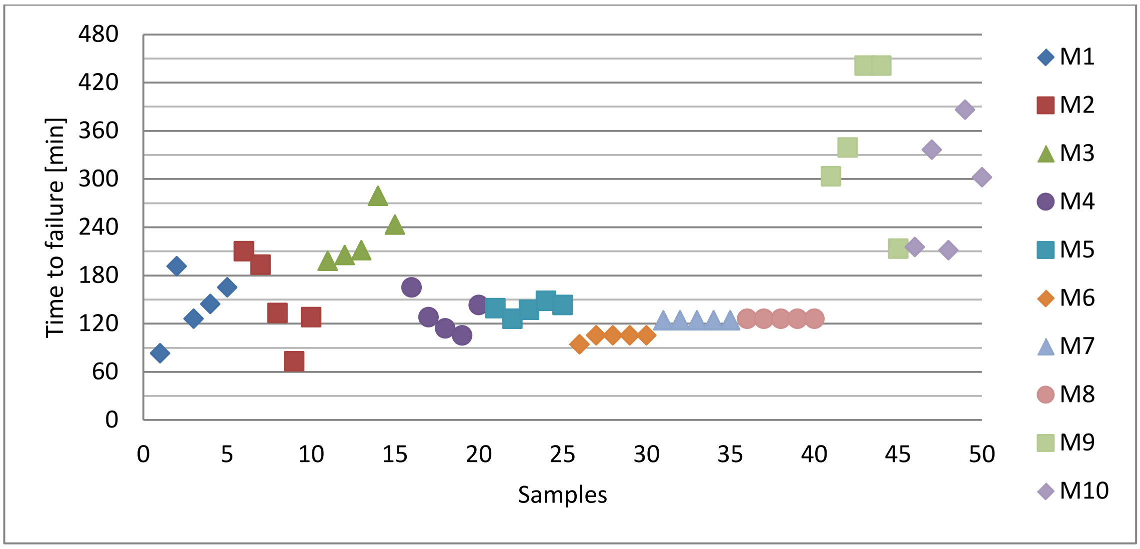


Figure 25: Material samples after a tracking test

Ten different materials were tested. Materials M1 to M8 are all samples from different heat shrink tubes used in medium voltage terminations. M9 and M10 are material samples manufactured from the same silicon type that is used in one of the cold shrink terminations.

The standard requirement to pass this test is that all five material samples should withstand two 60 minute steps before failure. Since the idea was to compare the performance of different materials the test was continued further, until all five samples had failed according to the standard requirements.

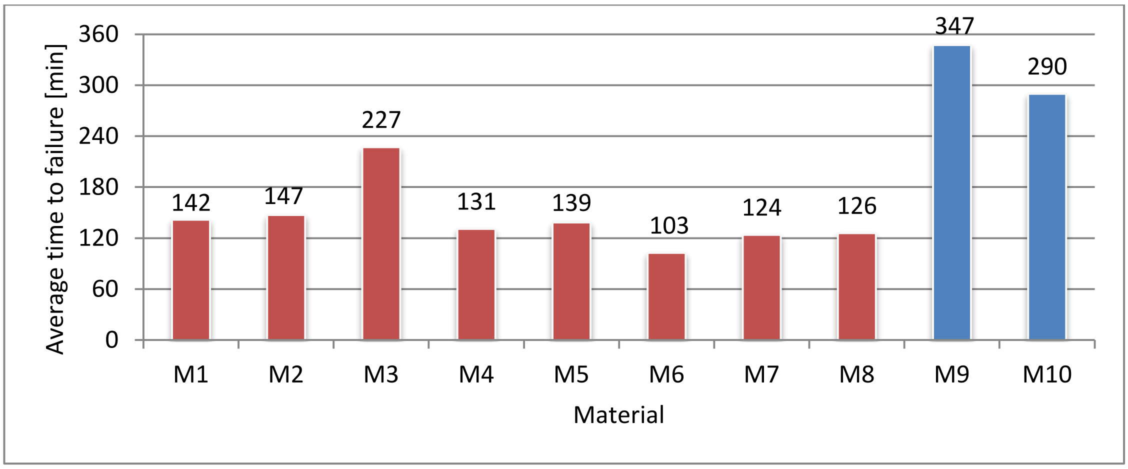
The test results for all ten materials are presented in Graph 10. The results for M6, M7 and M8 are clumped up, because these tests had to be stopped at these points when samples had ignited inside the test chamber.



Graph 10: Tracking test results for materials M1 – M10

Clear performance differences can be seen between the tested materials. Especially the difference between the heat shrink and cold shrink materials is obvious. The heat shrink materials failed at voltages between 3.0 and 3.75 kV at test times between 73 and 279 minutes. The silicon samples from the cold shrink terminations failed at voltages from 3.5 to 4.5 kV at test times between 211 to 441 minutes.

The results contain some deviance between samples of the same material, so for easier comparison, an average time to failure is presented in Graph 11.



Graph 11: Average time to failure

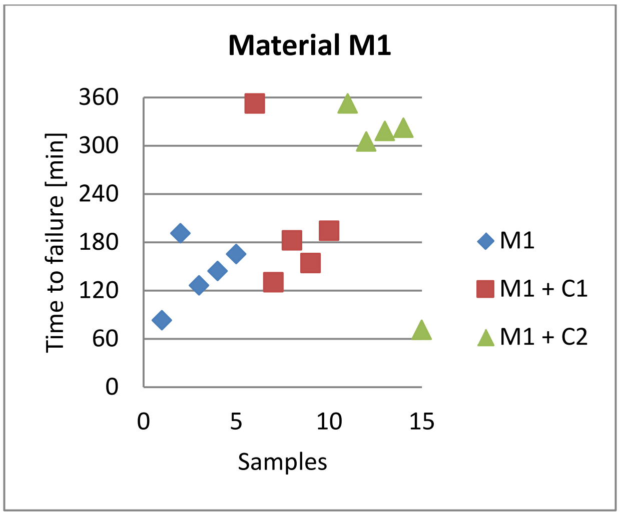
The average time to failure graph shows quite similar performance for most of the heat shrink materials. Material M3 differs mostly from the others with clearly better performance.

When the results are inspected from the standard point of view, more variance can be seen between these materials. Materials M1, M2, M4 and M6 did not pass the requirement of two full 60 minute steps without failure, to reach the 3.0 kV voltage class. Materials M5, M7 and M8 all fulfilled the requirement for Class 2A 3.0 and material M3 fulfilled even the requirement for Class 2A 3.25.

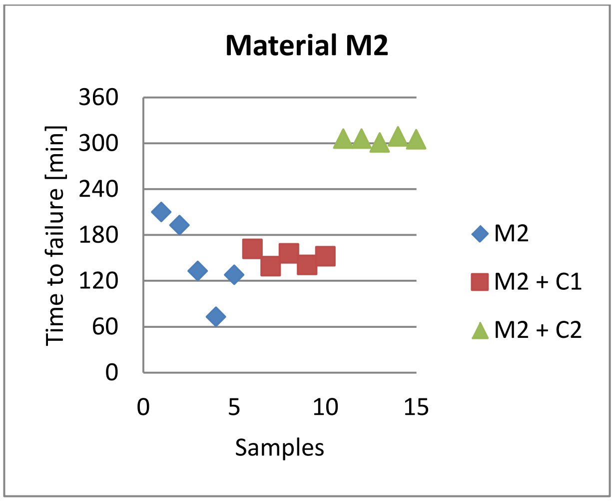
Both cold shrink materials M9 and M10 fulfilled the requirement for Class 2A 3.25. Starting the test at a higher voltage could result in an even higher voltage class for these silicon samples.

In addition to studying the performance differences between materials, two coating types were also tested. The aim was to find out if the performance of existing heat shrink terminations could be improved by applying some type of coating on top of the material. This was tested by applying a layer of coating on top of certain heat shrink samples and the tracking test was performed again for these treated samples.

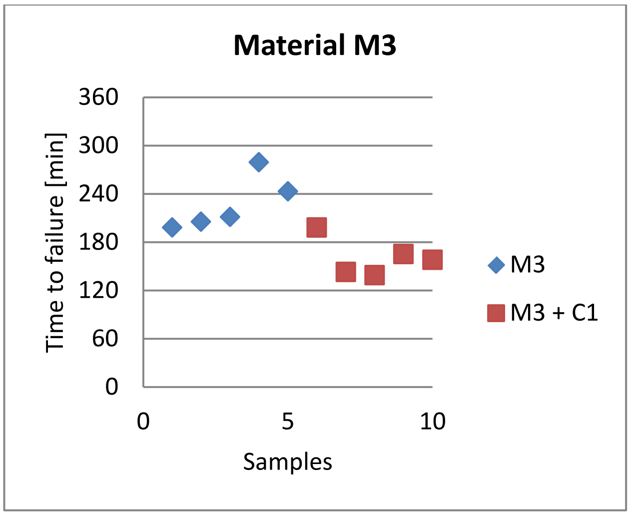
Coating C1 was tested with materials M1, M2 and M3 and coating C2 was tested with materials M1 and M2. The results for these tests are presented in Graph 12, Graph 13 and Graph 14.



Graph 12: Effect of coatings C1 and C2 on material M1



Graph 13: Effect of coatings C1 and C2 on material M2



Graph 14: Effect of coating C1 on material M3

The performance difference for coating C1 shows a slight improvement in average results with materials M1 and M2. With material M3 however, the performance is decreased. The main difference with the coated material samples is that all fulfilled the standard requirement for Class 2A 3.0.

The general performance of the samples treated with coating C2 was significantly better than the performance of any other heat shrink sample. The only exception was one of the C2 threated samples of material M1, which failed after 71 minutes. This failure is expected to be caused by an impurity in the material rather than caused by the coating itself. This expectation is based on the fact that all other C2 coated samples failed after a significantly longer test time and the performance of all these samples was also very uniform.

These results indicate that the resistance against surface erosion and tracking can clearly be improved on certain heat shrink materials by using correct type of coating on the surface of these materials. The main reason for using a coating on top of the terminations surface is to make the material more repellent against moisture and pollutants and thereby also to prevent the surface discharges from occurring. Because of this, the aim of this test is not to see how much the performance can be improved by the coating, but to check that the performance is at least not decreased drastically if discharges would occur.

4.2 Salt fog test

The performance of different medium voltage terminations was compared in a salt fog test. The test was performed in an external high voltage laboratory with a big salt fog chamber that allowed simultaneous testing of several medium voltage terminations.

The aim of the test was to study the lifetime expectancy of terminations subjected to harsh environmental conditions where continuous surface discharges occur for longer periods. The duration of the standard salt fog test is 1000 hours, but this test was run for 2500 hours. Except for the test duration, the procedure was otherwise performed according to the standard salt fog test procedure. The tested terminations were single-core terminations with a rated voltage of 12.7/22 (24) kV. The test voltage was 16 kV (1.25U_0) and the conductivity of the water was 1600±200 mS/m.

Four indoor termination types and two outdoor termination types were included in this test. The numbering, naming and the type of the tested terminations differ from the previously mentioned inspection case terminations.

The following termination types were tested:

- SF_T1: Heat shrink indoor termination
- SF_T2: Heat shrink indoor termination
- SF_T3 Heat shrink indoor termination
- SF_T4 Cold shrink indoor termination
- SF_T5 Heat shrink outdoor termination
- SF_T6 Heat shrink outdoor termination
- SF_T7 Cold shrink outdoor termination

All the tested terminations performed surprisingly well in this extended test. Because of the relatively equal performance, individual results are not examined more closely.

The salt fog test is only required for outdoor terminations, but no significant difference could be seen between the indoor and outdoor terminations after the test. Based on this, it seems that the increased creepage distance is not so important regarding the termination performance in the salt fog test. What seems to be more important is how well the materials can withstand tracking and erosion caused by the constantly occurring surface discharges. In other words it means that the salt fog test does not give a clear indication of the performance differences between various termination types in real operating environments. Instead, it could indicate if the materials used in the terminations offer sufficient tracking resistance in harsh conditions.

The main outcome of this test was that even if the test duration is increased significantly above the standard requirement, all the tested termination types could still be used in normal operating conditions. Because of the increased test duration, the surface of all terminations was naturally more eroded than after a normal 1000 hour salt fog test and the terminations would therefore not pass the standard requirement.

On all the tested heat shrink terminations the erosion was mainly concentrated above the cut edge of the insulation screen. Most of the terminations had also eroded traces of dry bands randomly spread along the surface. The cold shrink termination types SF_T4 and SF_T7 had clearly less traces of erosion visible on the surface than all the tested heat shrink termination types. Samples of uncleaned terminations after the 2500 hour test are shown in Figure 26.

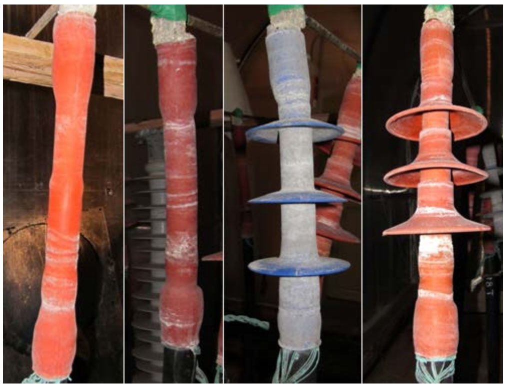


Figure 26: Uncleaned terminations after the 2500 hour salt fog test

The results from this extended salt fog test shows that all tested termination types are capable of withstanding continuous surface discharges for significantly longer durations than what the standard salt fog test requires. Based on this, it can also be expected that the terminations operating in real network conditions can also withstand long periods of continuous surface discharges without any imminent risk for termination failure.

Regardless if the terminations perform well in the salt fog test, the test does not give any real indication on how the accessories perform in a real operating environment. This is because of the fact that continuous changing of dry and wet periods takes place in real outdoor conditions. During the dry periods the materials can recover their surface hydrophobicity, which improves remarkably the resistance against surface discharges. Because of the salt fog test procedure, the continuously ongoing spray of salt fog suppresses completely the effect of the hydrophobicity. [28]

The loss of hydrophobicity can be examined by measuring the leakage current during the salt fog test. Because of the high conductivity of the sprayed solution, the loss of hydrophobicity is the same regardless of the creepage distance for similar terminations. The leakage currents for three similar terminations with different voltage ratings are presented in Figure 27. [28]

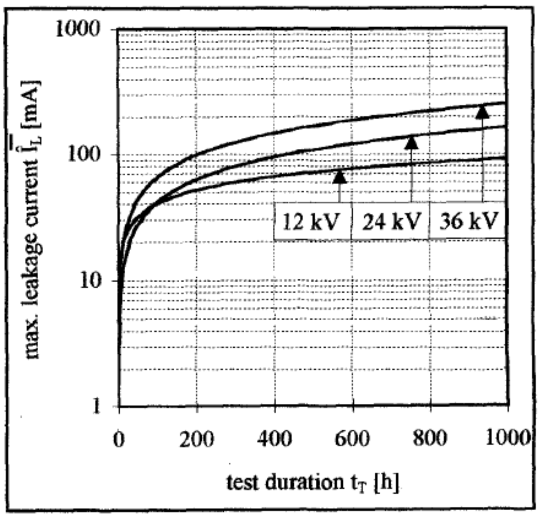


Figure 27: Comparison of leakage currents during a salt fog test [28]

According to these results the hydrophobicity is lost almost immediately in the beginning of the test, regardless of the voltage rating of the accessory. This behavior could also explain why the performance of the indoor and outdoor terminations is similar in the extended salt fog test, even if the creepage distances vary.

The results from the salt fog test clearly indicate that other test methods are needed to study the real life performance of medium voltage terminations.

4.3 Fog chamber test

A small fog chamber was built in order to perform experimental high voltage tests for various medium voltage terminations. The main chamber was manufactured from plastic with a sealable acrylic glass window on one side of the enclosure. The enclosure was designed so that three single-core terminations could be tested simultaneously. The chamber was equipped with a spray nozzle for producing atomized water spray, by mixing pressurized air and a liquid solution. Both the air pressure and the liquid flow were adjustable. The chamber was equipped with three sealable bushings for inserting the cable and the terminations. The terminations were similarly lined inside the chamber, as they would be inside a secondary outdoor substation.

The initial steps of the surface discharge phenomenon could be studied by performing partial discharges measurements in a sealed chamber like this, where one end of the tested cable is outside of the enclosure. The fog chamber is presented in Figure 28 with an experimental partial discharge test setup.

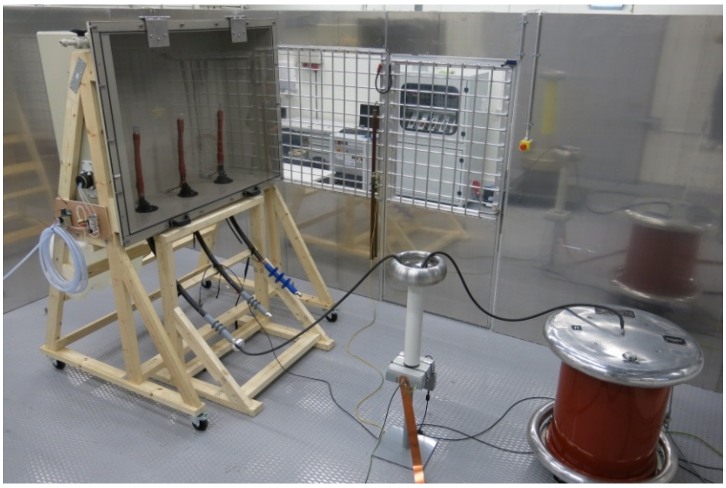


Figure 28: Test chamber for experimental surface discharge tests

4.3.1 Experimental PDIV step test

Partial discharge tests were performed in the fog chamber to study the partial discharge inception voltage (PDIV) for different unaged termination types. The test was done for two indoor termination types and two outdoor termination types. The termination types were selected so that both heat shrink and cold shrink terminations were tested. The heat shrink indoor termination has no rain sheds at all and the outdoor termination has three rain sheds. The cold shrink indoor and outdoor terminations both have rain sheds included in the termination body.

The numbering and naming of the tested terminations differ from the previously mentioned ones from the inspection cases and the salt fog test. The following termination types were tested in the experimental fog chamber tests:

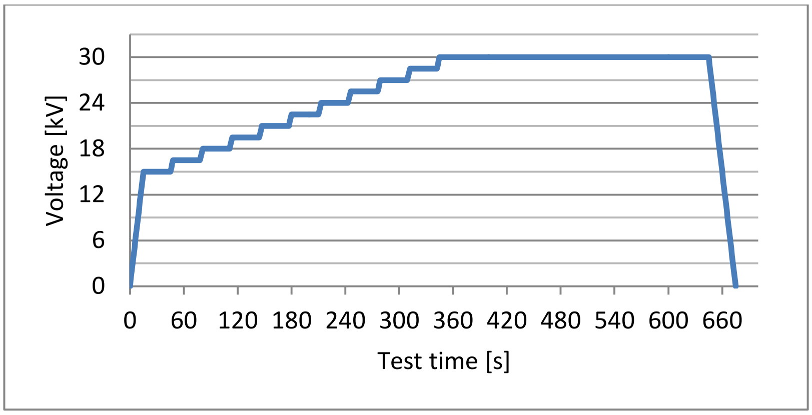
FC_T1	Heat shrink indoor termination
FC_T2	Cold shrink indoor termination
FC_T3	Heat shrink outdoor termination
FC_T4	Cold shrink outdoor termination

Three terminations of each type were tested. Each termination was tested separately in the middle of the fog chamber. All terminations were positioned in the same way inside the chamber, so that the cable lug was at exactly the same height in all tests.

The contaminant was produced by mixing ionized water with a suitable amount of ammonium chloride so that the conductivity of the liquid was approximately 1600 mS/m. The contaminant was sprayed into the chamber with a rate of about 0.4 $l/h/m^3$. The spray was kept on for 15 minutes before starting the voltage test for each termination, to fill the chamber with a uniform layer of fog. The chamber was cleaned and dried properly between each test and the test setup was checked to be free of partial discharges up to a voltage level of 30 kV before starting the fog spray.

The voltage application and the step times were controlled automatically to ensure a similar test procedure for each termination. The partial discharge peak value was also measured automatically with 1 second intervals throughout the whole test duration.

The voltage was first increased from 0 to 15 kV and kept at this level for 30 seconds. From here on, the voltage was increased with 1.5 kV steps up to 30 kV with a 30 second hold at each voltage level. The 30 kV voltage level was then kept for 5 minutes before ending the test. The voltage steps are presented in Graph 15.



Graph 15: PDIV test voltage steps

Partial discharge values were recorded throughout the whole test for each termination. Based on this recorded discharge data, the voltage level where the continuous discharges started was noted. Random discharge peaks were seen during most of the tests but individual peaks were ignored, as the aim was to find out the actual voltage level where continuous surface discharges start on the termination surface.

The results from the partial discharge inception voltage step test are presented in Table 23.

Table 23: Test results for PDIV step test

Termination	Sample	FC_T1	FC_T2	FC_T3	FC_T4
PDIV [kV]	1	> 30.0	21.0	16.5	27.0
	2	30.0	22.5	18.0	25.5
	3	> 30.0	21.0	18.0	28.5
Average PDIV [kV]		*30.0*	*21.5*	*17.5*	*27.0*

The results show very even performance for the same type of terminations. The measured PDIV values for the three terminations of the same type are not more than 3.0 kV apart for any of the tested termination types. This indicates that the initial stage of the discharge occurs similarly in the same type of terminations in this kind of an environment. A lot of variation is seen between the PDIV results for the different termination types. The ranking was however slightly surprising, as the heat shrink indoor terminations had clearly the highest PDIV values and the heat shrink outdoor terminations had the lowest values.

The rapid increase of voltage could have some effect on this behavior, but the expectation was still to see some correlation between the inception voltage and the creepage distance of the terminations. The creepage distances for the tested terminations are presented below:

FC_T1	340 mm	(Insulator Pollution Class 0)
FC_T2	325 mm	(Insulator Pollution Class 0)
FC_T3	605 mm	(Insulator Pollution Class 3)
FC_T4	555 mm	(Insulator Pollution Class 2)

These results clearly indicate that the PDIV is not dependent on the creepage distance of the termination in this kind of an environment. It seems more like the shape of the termination surface is the crucial factor affecting the inception voltage in a sealed enclosure, filled with highly conducting fog. To verify the expectation, an additional termination type was tested.

The influence of the termination shape was tested by installing a silicon rain shed on all three FC_T1 terminations. The results for these three additional samples are presented in Table 24.

Table 24: Test results for additional test with FC_T1 termination

Termination	Sample	FC_T1 + rain shed
PDIV [kV]	1	22,5
	2	24,0
	3	24,0
Average PDIV [kV]		*23,5*

The expectation seems to be correct, as the inception voltage level of FC_T1 decreased significantly after adding the rain shed. The reason for this behavior has to be related to the water drops that are stuck on the upper edge of the rain shed. Regardless of the high hydrophobicity of the silicon, the droplets get stuck on this horizontal surface on the top of the rain shed and discharges ignite. The water droplets on the rain shed can be seen in Figure 29.

Figure 29: Water droplets on the edge of the rain shed

Based on these results, the shape of the termination surface has significant effect on the PDIV voltage in an enclosure filled with highly conducting fog. The outcome of this test is however not very well in line with the results obtained from the field inspections, as the outdoor terminations with longer creepage distances generally perform better in outdoor environments. The PDIV step test results could still be used to indicate what kind of a termination designs works best in high pollution environments with airborne particles. The sleek termination designs have a smaller surface for pollution build up and could therefore work better in these kinds of environments. The drawback of such designs could however be the insufficient creepage distance since the total length of the termination is often limited.

More tests were performed to study the effect of the surface hydrophobicity because a short test like this did not give good indication of the creepage distance dependency to the termination performance in real operating environments.

4.3.2 Effect of surface hydrophobicity

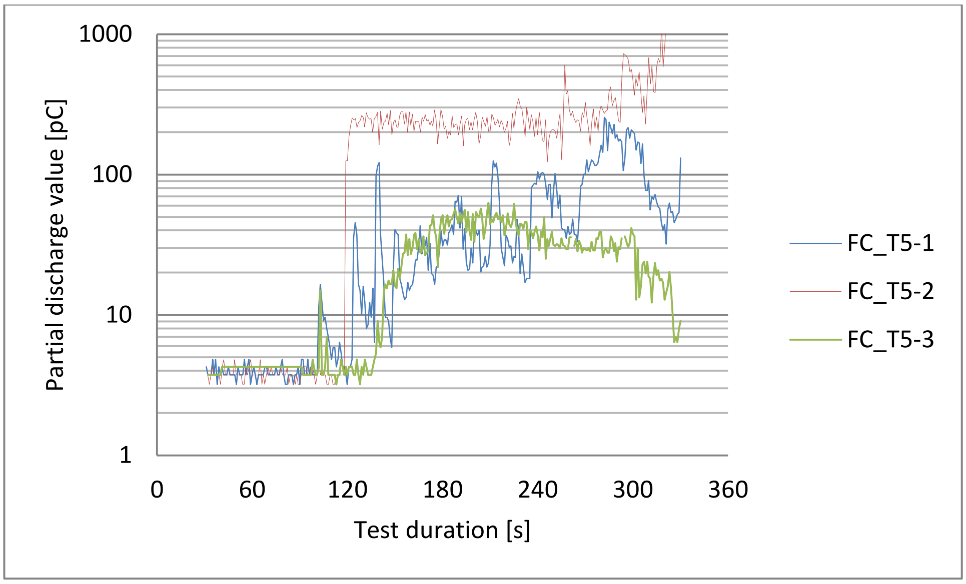
The effect of surface hydrophobicity was tested with three new heat shrink terminations. The tests were performed with indoor terminations which had no rain sheds. The surface of the terminations was made hydrophilic by using grinding paper, as shown in Figure 30. This was done to assure the occurrence surface discharge during the test.

Figure 30: Grinded FC_T5 termination surface

The test procedure was changed slightly because the inception voltage was so high for the terminations without rain sheds.

The voltage was increased directly from 0 to 30 kV and then kept there for 5 minutes. The conductivity of the contaminant was the same as in the PDIV step test, but the application of the spray was increased to approximately 1.0 l/h/m^3. Another change was that the voltage was applied directly after starting the fog injection. The chamber was also cleaned and dried between each sample in this test and the test setup was checked to be free of partial discharges up to 30 kV before starting the test.

The test was first performed for the three newly assembled terminations with the grinded surface. The discharge occurrence during the test is presented in Graph 16 for these three samples.



Graph 16: Discharge occurrence vs. test duration for the tested FC_T5 terminations

Quite much variation can be seen in the discharge level between the three tested samples. Regardless of the variation in discharge magnitude, the time to discharge inception is relatively similar for all three samples.

The aim was to study the effect of the surface hydrophobicity, so the same procedure was repeated after applying a layer of coating C1 on the surface of these same three terminations. The coating increases the surface hydrophobicity which should therefore also increase the PDIV value for the termination.

This application of the coating on the surface of the terminations lead to a completely discharge free assembly throughout the whole test duration for all three samples. The results for both test setups are presented in Table 25.

Table 25: Test results for FC_T5 terminations

Termination	Sample	FC_T5	FC_T5 + C1
Time to discharge inception [s]	1	70	> 300
	2	87	> 300
	3	107	> 300

The difference between these two test setups is evident. With a hydrophilic surface the time to discharge inception is increased over the 5 minute test duration whereas all the original samples had discharges occurring already before 2 minutes at the 30 kV level was full.

Based to these results, the performance of same type of terminations can be clearly improved with a more hydrophobic surface that repels moisture and pollutants.

4.4 Assessment of laboratory test results

Three different types of laboratory tests were performed to study the surface discharge phenomena and also the performance of various medium voltage terminations.

The resistance to tracking was first studied for various surface materials used in the terminations and then by subjecting the terminations to an extended salt fog test. Experimental partial discharge measurements were also performed in a small fog chamber to study the discharge inception procedure in a high humidity environment and the influence of surface hydrophobicity to the discharge occurrence.

Tracking test

The main outcome of the tracking tests was that the tested cold shrink materials had a significantly better resistance to tracking and erosion than what the heat shrink materials have. The results from this same test also indicated that the tracking resistance of certain heat shrink materials could be improved by applying a layer of coating on the surface of the material.

Salt fog test

The extended salt fog test demonstrates well that all tested termination types can withstand long-lasting surface discharges without significant damage to the accessory. Another outcome of this test was that the creepage distance of the termination is irrelevant regarding the performance in this test. This behavior clearly indicates that the real life performance of these terminations cannot be evaluated based only on the salt fog test and other test methods should therefore be evaluated.

Fog chamber test

The correlation between the creepage distance and the termination performance in harsh environments could not be verified in the short duration fog chamber tests. The surface discharge inception voltage can still indicate how moisture and contaminants stay on the surface of certain termination designs in polluted environments. Also the performance improvement in harsh environments with a more hydrophobic surface was demonstrated in these fog chamber tests.

5 Conclusions

The aim of this thesis was to study the surface discharge phenomena in medium voltage cable terminations. Surface discharges can occur on the surfaces between the high voltage and ground electrodes. Traces of discharges are often seen on accessories located in various outdoor environments, especially inside unheated enclosures and in polluted areas. Regardless of this relatively common phenomenon, reasons for these discharges are generally not very well understood by the people working in the field. One of the goals was therefore to increase the general knowledge of the discharge phenomena and thereby also avoid possible problems in future assemblies.

The field performance of existing termination types was studied by analyzing data from inspections that were performed for terminations used inside secondary outdoor substations. The inspection results indicated that performance differences do occur between various terminations types and substation models. The data also revealed that the common practice is to use indoor terminations inside these substations, regardless of the tough operating environment that can occur in an unheated outdoor enclosure. The operating conditions inside these enclosures are actually worse than in a normal outdoor environment, since the washing effect of rain is removed by the structure. The enclosure does offer protection against rain and solar radiation, but the accessories are still subjected to condensed moisture and environmental pollutants. The surface discharge issues are mainly related to these challenging environmental conditions. Also the space restrictions inside the enclosure can lead to use of wrong accessory types and inappropriate installation. Proper heating of heat shrink materials seems to be one of the main challenges inside tight enclosures. Cold shrink terminations are not affected by the issues related to heating and could therefore offer a convenient solution in these places.

Laboratory tests were performed to verify the tracking resistance of the generally used termination types. The test results indicated that the performance of all the tested termination types was sufficient to withstand the occurrence of long-lasting surface discharges. Performance differences were however seen in the tracking test between various surface materials. The silicon materials used in the cold shrink terminations performed clearly better in this test than any heat shrink material. These results also indicated that the performance of certain heat shrink materials could be improved by applying a coating on the surface.

The performance improvement of an increased surface hydrophobicity was also studied in an experimental fog chamber test. The result from this test indicates that the partial discharge inception voltage can be increased by improving the surface hydrophobicity of the termination. Another outcome of this test was that the shape of the termination surface affects the pollution build up on the termination surface which can be seen in the inception voltage values. The correlation between the creepage distance and the performance in real operating conditions could however not be verified in this test. The results from the field inspections clearly indicate that the outdoor terminations with longer creepage distances perform much better in harsh outdoor environments. None of the tests performed did however show any indication of this behavior. Most surprising was that even the salt fog test failed to indicate clear performance differences between indoor and outdoor terminations. Based on the field inspection results and these test results, the validity of the whole salt fog tests can be questioned. The salt fog test alone does not seem to be sufficient for ensuring the required performance for medium voltage terminations subjected to harsh outdoor environments. Because of this, other test methods should also be considered to ensure a long service life for the accessories used inside unheated outdoor enclosures. The changes in the climatic conditions should somehow be considered to better simulate the real operating environment with varying dry and wet periods.

The outcome of this thesis was that the surface discharges on medium voltage terminations are mainly caused by moisture and airborne contaminants. These two components lead to an increased leakage current over the termination surface, which eventually starts the discharge process. The leakage current can be limited by an increased creepage distance, improved hydrophobicity or even by using termination shapes that reduces the pollution build-up. The terminations cannot often be completely protected from the environmental contaminants, but the condensation inside these outdoor enclosures could probably be decreased by changed building practices for the foundations.

Increased awareness of the discharge phenomena can help in selecting correct termination types for nonstandard service conditions and therefore assure a longer service life for the accessories. Based on the inspection results, the majority of surface discharges could have been avoided if outdoor terminations or cold shrink terminations would be used in the inspected substations. Existing installations can be improved by increasing the creepage distance with rain sheds or improving the hydrophobicity of the surface with coatings.

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