Development and Trends of Ceramic Solid-Core Station Post Insulators for UHVAC Outdoor Applications

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Thomas Morocutti

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Institut für Hochspannungstechnik und Systemmanagement
Technische Universität Graz
Inffeldgasse 18, A - 8010 Graz

PPC Insulators Austria GmbH
Gamserstraße 3, A - 8523 Frauental an der Laßnitz

Begutachter: Em.Univ.-Prof. Dipl.-Ing. Dr.techn. Dr.h.c. Michael Muhr
Betreuer IHS: Dipl.-Ing. Thomas Berg
Betreuer PPC Insulators: Dipl.-Ing. Gustav Gödel

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Abstract

The main purpose of this work is to research the development and trends regarding high voltage ceramic solid-core post insulators for UHVAC applications over the last decades. Furthermore it also represents the performance analysis of new ceramic post insulators in a shorter non-standard design as well as their agreement with the IEC standards. At first glance, high voltage insulators seem to work as a simple, none conducting, (mechanical) spacing device between two electrically conducting parts with different voltage levels. Insulators are however quite the opposite and much more complex. Finding a non-conducting material is a minor problem in designing insulators. The tricky part is to develop insulators with an exceptionally high level of reliability over decades, regarding to their exposed environmental influences. This work summarizes the electrical, mechanical and chemical influences which have to be considered during designing insulators. The air surrounding the insulator and the interface between the insulator and the surrounding air represent challenges for insulators design. The air normally has a lower electrical strength than the insulator itself. The influence of the atmospheric pressure and the ions produced at the conductors' ends could lead from micro flashing to a total flashover. The interface can also reach a high level of electrical conductivity. The resulting current and furthermore the ions in the air decrease the electrical strength of the surrounding environment, increasing the risk of flashover. The major focus of the development dealing with a technically and economically optimized insulator are the maximization of the insulating/arcing distance including length, mechanical strength and stiffness. Additionally the minimization of the mean and core diameter including weight, while maximizing the form factor are essential elements to consider. Furthermore the optimal shed profile needs to be elaborated. Another issue is the coating which is essential to retrieve the best performance of an insulator. Due to a more sophisticated manufacturing process high voltage insulators can be produced in bigger dimensions with thinner sheds than 40 years ago. The results are a longer arcing distance, less weight and most of all less electrically conducting parts. 40 years ago, the column design for a 800 $kVac$ post insulator was a chain of 6 tapered insulators, today just 2 insulators are needed to reach the same height. The main question which shall be answered within this work is: Do insulators need to have the same total height as 40 years ago, even if there are less conducting parts, or is it possible to reduce the height, yet still achieve the same level of insulation?

Keywords: Ceramic Solid-Core Station Post Insulator, Optimized Shed Profile, Optimized Form Factor, Norm Conformity

Kurzfassung

Das Ziel dieser Arbeit ist die Untersuchung der Entwicklung und Weiterentwicklung von Freiluft-Stützisolatoren aus keramischem Werkstoff für Höchstspannungsanwendungen. Des Weiteren werden Betriebseigenschaften von neuen Keramik-Stützisolatoren in kürzerer, nicht der Norm entsprechenden Ausführung, in Übereinstimmung mit den IEC Normen getestet. Auf den ersten Blick scheinen Hochspannungsisolatoren als simple, mechanische Distanzhalter zu arbeiten, die zwei leitende Teile mit unterschiedlichem Potential trennen. Bei genauerer Betrachtung sind die Anforderungen an Isolatoren aber viel komplexer. Ein nichtleitendes Material zu finden ist ein eher geringes Problem bei der Konstruktion von Isolatoren. Die Finesse besteht in der Entwicklung von Isolatoren mit einer außerordentlichen Ausfallsicherheit über Jahrzehnte hinweg, einschließlich deren Beständigkeit gegen äußere Umwelteinflüsse. Diese Arbeit fasst die elektrischen, mechanischen und chemischen Einflüsse zusammen, welche bei der Konstruktion berücksichtigt werden müssen. Die Umgebungsluft des Isolators und die Grenzschicht zwischen Isolator und Luft stellen die Herausforderung bei der Konstruktion von Isolatoren dar. Die Umgebungsluft hat normalerweise eine geringere dielektrische Festigkeit als das Isolatormaterial. Der Einfluss des Luftdrucks und der Ionen, produziert an den Elektroden, kann von einzelnen Teilentladungen, bis hin zu einem totalen Überschlag führen. Die Grenzschicht kann ebenfalls stark leitfähig werden. Der resultierende Kriechstrom und vielmehr die Ionen in der Luft verringern die dielektrische Festigkeit der Umgebung und erhöhen gleichzeitig das Risiko eines Überschlags. Der Entwicklungsfokus bei der Herstellung eines technisch und ökonomisch optimierten Isolators ist die Maximierung der Isolierstrecke, inklusive Länge, mechanischer Stärke und Festigkeit. Zusätzlich stehen die Minimierung des Kerndurchmessers, bei Maximierung des Formfaktors im Vordergrund. Des Weiteren muss das optimale Schirmprofil berücksichtigt werden. Ein anderes Problem ist die Beschichtung, welche wesentlich für die Performance eines Isolators ist. Mittels des heute verwendeten Herstellungsprozesses können höhere Hochspannungsisolatoren mit dünneren Schirmen als noch vor 40 Jahren produziert werden. Das Resultat ist eine längere Isolierstrecke, weniger Gewicht und vor allem weniger leitende Teile. Vor 40 Jahren benötigte man für einen 5700 mm langen Isolator 6 Teilstücke, heute ist es möglich, dieselbe Höhe mit 2 Isolatoren zu erreichen. Die Frage, die mit dieser Arbeit beantwortet werden soll ist: Müssen Isolatoren die gleiche Gesamthöhe haben wie vor 40 Jahren, auch wenn weniger Armaturen benötigt werden? Oder anders gesagt, ist es möglich, die Gesamthöhe einer Isolierkette, bei weniger Teilisolatoren, zu verringern und dabei die gleiche Isolationsfestigkeit beizubehalten?

Schlagwörter: Ceramic Stützisolatoren, optimiertes Schirmprofil, optimierter Formfactor, IEC and ANSI Normkonformität

Abbreviations

H magnetic field strength

J magnetic polarisation

E electric field strength

D electric flux density

ρ space charge

B magnetic flux density

ϵ_r relative permittivity

ϵ_0 absolute permittivity of vacuum

ϕ scalar potential

L_{PD} puncture distance

L_{arc} arcing distance

L_{CD} creepage distance or leakage distance

c shed clearance

S shed spacing - vertical distance between two similar points on successive sheds

P shed projection - the maximum shed overhang

d the straight air distance between any two points on the shed surface

l_d the creepage distance between the two points that define d

l_S the creepage distance between the two points that define S

CF creepage factor

PF profile factor

F_f form factor

α upper shed angle

β lower shed angle

DDDG directional dust deposit gauge

DDGI-S dust deposit gauge index - soluble

DDGI-N dust deposit gauge index - non-soluble

Dm	dry months (for DDDG)
ESDD	equivalent salt deposit density
Fd	fog days (for DDDG)
NSD	non soluble deposit
NSDD	non soluble deposit density
PI	pollution index (for DDDG)
SDD	salt deposit density
SPS	site pollution severity
TOV	temporal overvoltage
USCD	unified specific creepage distance

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1 Introduction

The insulation of conductive materials is a major issue for planning electrical systems. An insulator is basically a non-conductive spacing device, separating two electrically conducting parts with different voltage levels. The cheapest insulation material and main dielectric used in high-voltage networks would be air. It is a good dielectric, self-restoring below the ionisation threshold but for obvious reasons it can’t be used as a mechanical spacing device.

For the design of "outdoor" insulators, adherence to the electrical field laws is essential. In addition to the electrical stress, thermal and mechanical factors have to be considered. To comply with all demands a homogeneous field load is aspired. It can be reached through constructive design of the electrodes and a suitable selection of the insulating material [1].

The material which can actual be used for the selected application depends on several parameters: What are the electrical, mechanical and chemical requirements, how good are temperature and frequency stability, what are the economic considerations, etc? For the insulation of high voltage applications these considerations reduce the list of solid materials basically to ceramic, glass and polymeric materials. These materials have the best requirements, considering their application. For the purpose of this paper, we want to focus on ceramic as the insulation material.

Insulating a few thousand volts in dry condition is possible for almost any solid non-conductive material, the finesse is performing the same task in damp or polluted conditions. Insulators play a highly critical role in energy transmission. Although insulators represent a lower cost compared to other electrical equipment in energy transmission, a failure can have serious economic consequences. Insufficient design considerations regarding insulation needs will cause inappropriate insulator selection. The result is additional maintenance costs, for example; more frequent washing or application of pollution performance [2].

1.1 Fundamentals of dielectric fields

1.1.1 Overview

Designing and constructing high-voltage apparatus requires experience in the application of the electric field laws. Mechanical, thermal and atmospheric conditions add additional challenges when trying to optimize construction from the high-voltage point of view. Design engineers have to find a compromise between technical and economical demands. A fundamental support are the safety levels in context of the insulation co-ordination. For a given insulation distance, the highest possible breakdown or flashover voltage as well as a field stress as homogeneous as possible are desired. It can be realized by the insulator design as well as the selection of the insulation material. Is the use of one insulation material not enough to ensure the dielectric strength, a combination of several materials has to be used [3].

An important factor for optimizing the insulation alignment is the knowledge of the electrical field and its spatial and temporal arrangement. Every electrode system has to be designed in a way, that the limit of the maximum field strength isn't exceeded at every point of the insulation. The manufacturer has to comply with this unconditional demand to avoid any kind of discharge. Therefore the determination of the field profile, inside and outside of the insulation arrangement, is necessary. Starting with the potential theory, the common methods of choice are the approximation solution using field catalogues or numeric methods [3]. To avoid unwanted effects like a high field strength or a non-linear voltage division also a homogeneous field stress is desired [1].

1.1.2 Fundamental laws

The field-theoretical point of view describes field problems for high voltage engineering as quasi-stationary fields. The four Maxwell equations [1.1 to 1.4] are considered to be generally applicable laws of electrodynamics which combine electric and magnetic values [4].

$$rotH = J + \frac{\partial D}{\partial t} \tag{1.1}$$

$$rotE = -\frac{\partial B}{\partial t} \tag{1.2}$$

$$divD = \rho \tag{1.3}$$

$$divB = 0 \tag{1.4}$$

Because there is no variation in time, the field calculations for high voltage engineering are considered to be the result of electrostatic fields. Maxwell's equations [1.5 to 1.8] simplify and the result is a separation of the magnetic and electric values, which can now both be handled separately [3].

$$rotH = 0 \tag{1.5}$$

$$rotE = 0 \tag{1.6}$$

$$divD = \rho \tag{1.7}$$

$$divB = 0 \tag{1.8}$$

Because of the fact that in quasi-electrostatic cases the magnetic field B in 1.2 is zero, the electric field E has a scalar potential ϕ and the equation changes to 1.9. Maxwell's equation of the electric flux density D in 1.7, combined with the material equation 1.10, leads to a new equation for the electric potential ϕ [5].

$$E = -grad\phi \tag{1.9}$$

$$D = \epsilon_r \epsilon_0 E \tag{1.10}$$

$$div(\epsilon_r \epsilon_0 grad\phi) = -\rho \tag{1.11}$$

The Laplace equation inside each medium is born by assuming an absence of space charge ρ and the dielectric constant ϵ_r to be constant inside each medium [5].

$$divgrad\phi = \delta\phi = 0 \tag{1.12}$$

1.1.3 Boundary conditions

For the description of the boundary conditions for dielectric configurations three conditions have to be considered. First, the so-called Dirichlet boundary condition, which constrains the electric potential on conductor surfaces to a constant value $\phi = \phi_0$. The other two conditions are for the interface of two dielectrics ϵ_A and ϵ_B. One condition is the continuity of the electric potential ϕ, or from another point of view the continuity of the tangential field strength E_t, the other is the continuity of the normal component D_n of the electric flux density [5].

$$\phi_A = \phi_B \tag{1.13}$$

$$E_{tA} = E_{tB} \tag{1.14}$$

$$D_{nA} = D_{nB} \tag{1.15}$$

$$\epsilon_A E_{nA} = \epsilon_B E_{nB} \tag{1.16}$$

1.1.4 Symmetric influence of single-layer dielectrics

Regarding the dielectric strength, there is a great difference between a symmetrical and asymmetrical electrode arrangement. For comparable striking distances and electrode curvatures, symmetrical electrode arrangements are better, because for a constant voltage the highest field strength E_{max} is lower than in asymmetrical arrangements. The intention, for an optimized design, is to minimize the highest field strength E_{max}. For single-layer dielectrics the field line with the highest stress is usually the shortest distance between electrodes. An important application of this knowledge is the installation of post insulators. For the same striking distance, the breakdown voltage can be increased if the earth sided electrode is installed at a higher place, also the influence of polarities is decreased [3].

$$U = \int_0^s E(x)dx \tag{1.17}$$

1.1.5 Multi-layer dielectrics

To increase the electric strength of an insulation system a combination of several insulating materials is used. The field lines get refracted at the interface of these materials in a way that

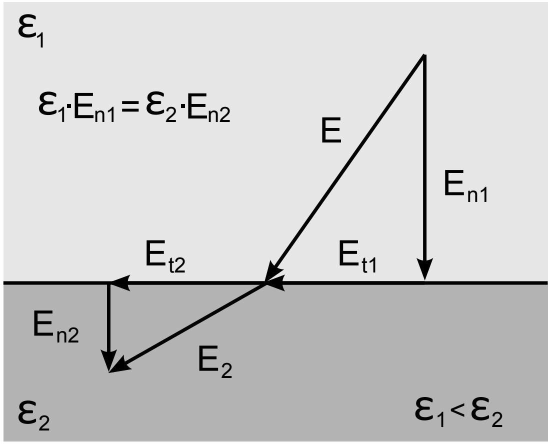


Fig. 1: Electrical field strength at the interface between two dielectrics [3]

the tangential component of the field strength stays continuous. The normal component results out of the demand of a continuous dielectric offset (Fig. 1) [3].

$$E_{t1} = E_{t2} \tag{1.18}$$

Because pollution and humidity cannot be avoided in most cases (pollution layer), a minor electrical stress of the interface is claimed. An important engineering task is minimizing the electric field strength at the interface, especially its tangential component. A beneficial case is if the interface is parallel to equipotential regions ($E_t = 0$), it is then called a transverse interface. For the insulator design a best possible adaptation of the barriers to the progression of the equipotential regions is called for [3].

At longitudinal interfaces the tangential component of the field strength has a finite value and the normal component is null. In this case the interface follows the progression of the maximal gradient (field line), the dielectrics have no influence on the field progression. An example is shown in figure 2. In arrangement 1) the tangential component is homogenised with the electrodes. In arrangement 2) the insulator design is adjusted to the field progression. In a technical arrangement it is not entirely possible to avoid inclined interfaces (E_t and E_n have finite values), an attempt to homogenise the electrical field stress should also be intended [3].

Surface conductivity and partial discharge may reduce or eliminate the field enhancement at the contact points [5].

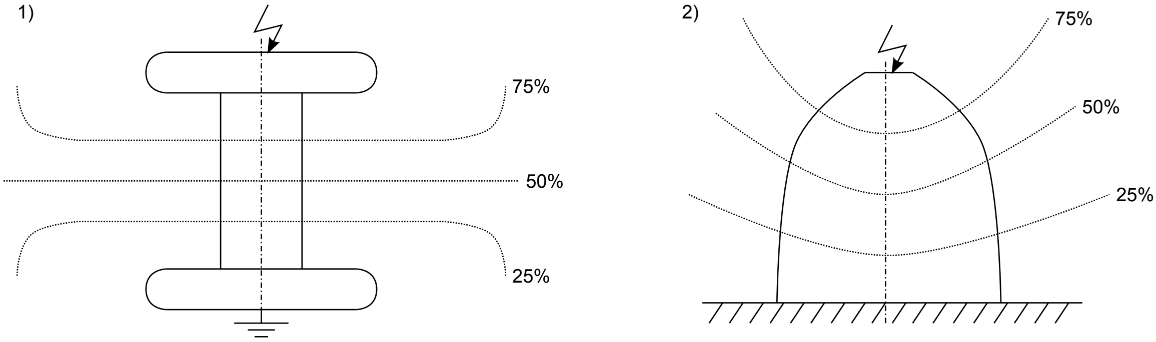


Fig. 2: Model arrangements of longitudinal interfaces [3]

1.1.6 Embedding effect

Arrangements with a field strength tending to zero or infinite frequently occur in high-voltage engineering. Field strengths tending to infinity appear near spikes or edges, field strengths that are tending to null appear at blind field spots or at drawn-in corners. Such discontinuities of the electric field typically appear at regions where electrodes and the differing dielectrics interfaces meet. The field distribution at dielectric edges is also discontinuous [1].

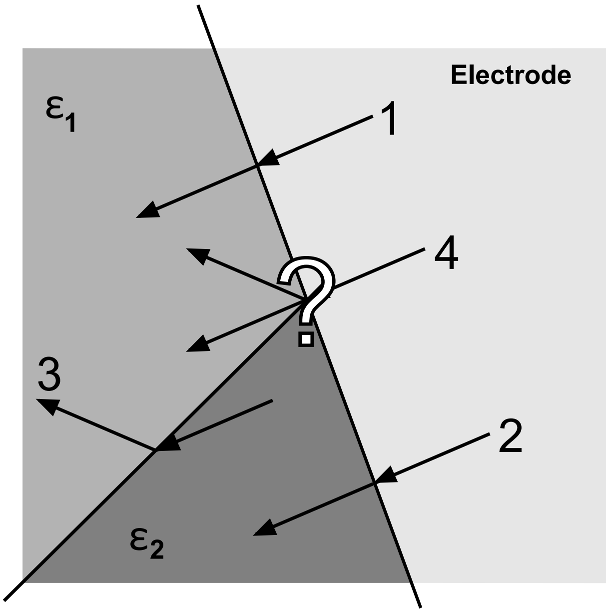
The triple-junction or triple-joint effect is a special phenomenon where three media meet: a conductor, a solid dielectric, and a gaseous dielectric (or a liquid, or a vacuum). If the contact area between the conducting electrode and the interface of neighbouring dielectrics isn't perpendicular, then two conflicting demands have to be fulfilled at the triple-joint. One is the orthogonality of the normal component, the other is the conformance with the law of refraction at dielectric interfaces [1, 5].

At the triple-joint the electric field has a singularity, at which the field strength is either tending toward null or infinity, depending on the embedding angle and the ration of permittivities. This phenomenon results from the equation of the electric field in 1.20 and the law of refraction in 1.21. As a result, both conditions cannot be fulfilled at the critical meeting point of the three materials at the same time [1].

$$rotE = 0 \tag{1.19}$$

$$E_{1t} = E_{2t} = 0 \tag{1.20}$$

$$\frac{\alpha_1}{\alpha_2} = \frac{E_{2n}}{E_{1n}} = \frac{\epsilon_1}{\epsilon_2} \tag{1.21}$$



Transition 1:	condition $E_{1t} \cdot \epsilon_1 = E_{2t} \cdot \epsilon_2$ can be fulfilled
Transition 2:	same as transition 1
Transition 3:	law of refraction is acting
Transition 4:	both conditions cannot be fulfilled at the same time, according to the rate of the permittivities the field strength diverges against null or infinite

Fig. 3: Embedding effect on dielectric interfaces [1]

1.1.7 Capacitive field control

To minimize the space of an insulation system, in compliance with the dielectric strength, a homogeneous field load is required. This can be achieved by measures to linearise the voltage distribution along the insulation distance. A different electrode design, the resistive field control and the capacitive field control are methods of choice. If an insulation arrangement has a small electrode curvature, in comparison to its striking distance, there is a high field strength near the electrodes. Through the capacitive field control of outer guard electrodes (cap and corona electrodes, arc protective fittings) a linearisation can be realized [3].

Theoretically, an insulator has a linear voltage distribution, because it's a serial connection of multiple partial capacitances (Fig. 4a). In reality, stray capacitances between the insulator and earth are interfering and a non-linear voltage distribution is the result (Fig. 4b). To antagonise this interference, methods for a capacitive field control are required. The use of control electrodes at the energised end of the insulation chain is linearising the voltage distribution along the

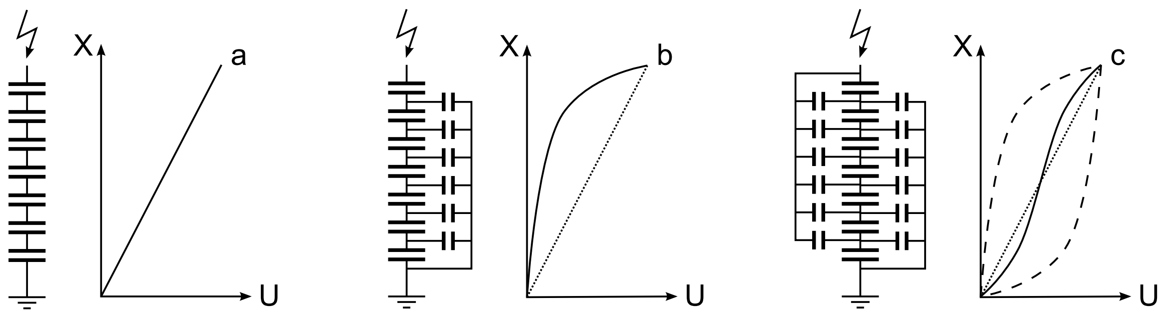


Fig. 4: Capacitive field control [1]

insulator. The resulting overall voltage is the sum of the two voltage curves (Fig. 4c).

1.2 Insulator types and characteristics

Outdoor insulators have a great variety in their applications, the most common types are shown in figure 5. Pin Insulators have been used since 1830 to insulate conducting wires up to 50 kV for physical support. Common materials used are porcelain, glass and resin. Cap-and-Pin Disc Insulators are used in a string to insulate suspended transmission lines, materials used are porcelain and glass. Bushings insulate conductors which pass through a partition, such as a wall or tank, materials used are porcelain, resin and composite materials. Composite Line Post Insulators, same as Line Post Insulators are used for suspension of overhead lines on a supporting structure, materials used are porcelain, glass, resin and composite materials. Long Rod Insulators, as well as Composite Long Rod Insulators are used to insulate overhead lines in suspension and strain positions, materials used are porcelain, resin and composite materials. Apparatus Insulators have a hollow body and they are mounted to apparatus to support conductors and insulate to ground, materials used are porcelain, glass, resin and composite materials [2]. The focus in this work is on the Porcelain Solid Core Station Post Insulators. They are intended to give rigid support in substations, equipment and bus-bars and insulate live parts from earth or other live parts. Other used materials are glass, resin and composite materials, but the focus is on porcelain.

1.3 Material considerations for insulators

To find the appropriate insulator for the specific application, it is important to know their material characteristics. Which material can actually be used for the selected application depends on several parameters: What are the electrical, mechanical and chemical requirements? How

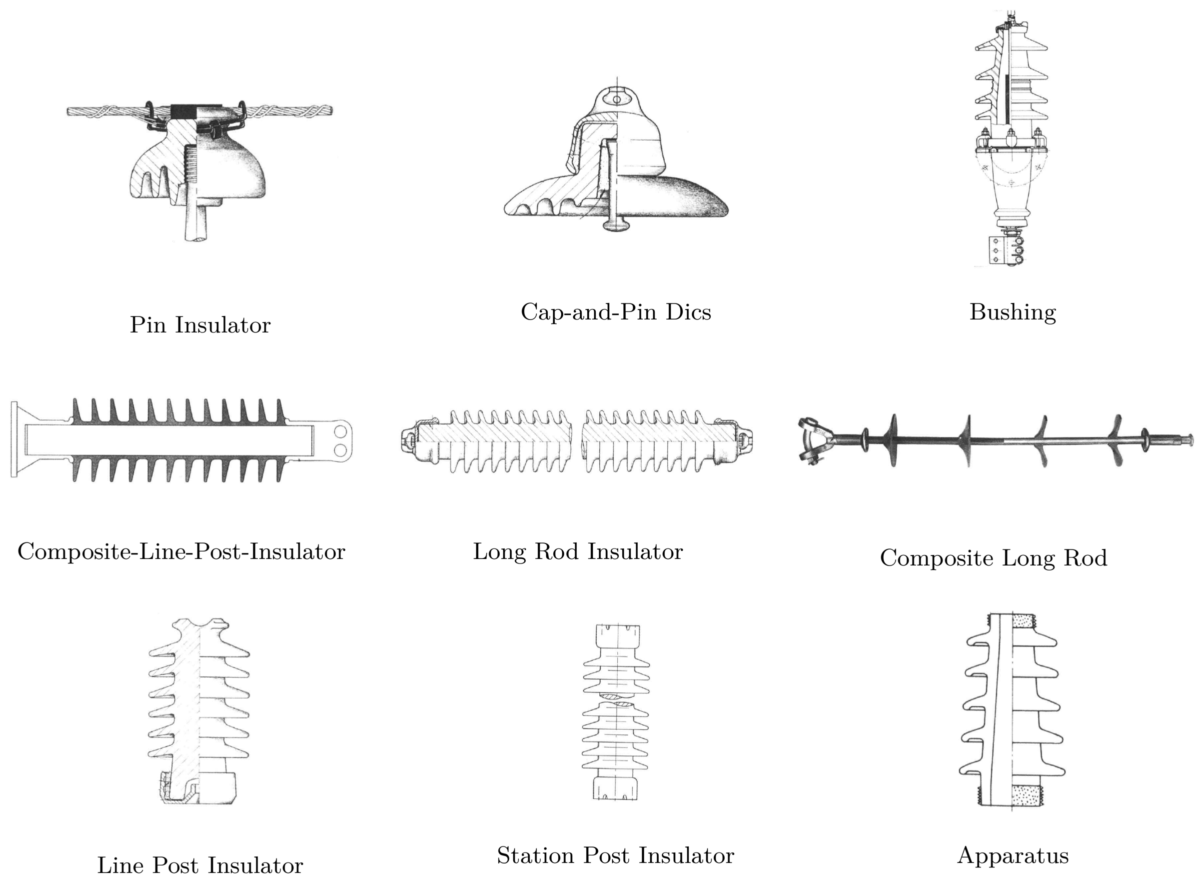


Fig. 5: Outdoor insulator types [2]

good is the temperature or frequency stability? What are the economical considerations? etc.

Insulating a few thousand volts in dry condition is possible for almost any solid non-conductive material, the finesse is performing the same task in damp or polluted conditions. A good insulator has to perform its duty over decades and should therefore keep an excellent dielectric capability, despite the often severe environmental influences. For the insulation of high voltage applications these considerations shrink this list of solid materials basically to ceramic, glass and polymeric materials. These materials have the best requirements, considering their application. For the insulation of high voltage applications the focus in this work lies on the use of ceramic as insulation material. Since its introduction in the mid 1800's, it is the most widely used material for outdoor insulation today. The compound of insulators is significantly influencing its performance, materials should be chosen wisely. In polluted areas, these differences of various materials become quite obvious. Characteristics, like hydrophobicity or the surface heating and grading current, serve to reduce the leakage current activity and the risk of flashover [2].

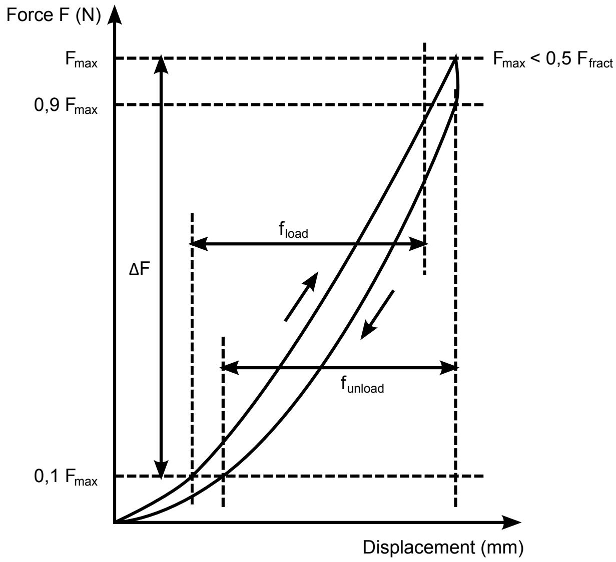


Fig. 6: Force-Displacement-Diagram for Young's modulus determination [7]

1.3.1 Mechanical considerations

A common way to determine the modulus of elasticity, the flexural strength, the breaking strain and the tensile stress in each direction is to determine the force-displacement-diagram (figure 6). All those values can be read from the diagram. With the curve progression it is also possible to identify the deformation behaviour. Ceramic, as a hard and rough material, has a steep curve progression. The modulus of elasticity is the quotient of force and displacement in the elastic region of the force-displacement-diagram. It is a measurement for the stiffness of materials and is determined through the bending test, the stretching test and sometimes the compression test. The flexural strength is the bending under four-point loading at breakage. In the test the subject undergoes tensile, compressive and transverse stress. The tensile stress is for determining the material behaviour at a one-way load, it depends on temperature and deformation rate [6].

1.3.2 Chemical and other considerations

The water absorption capacity strongly varies for the different insulating materials. Moisture badly influences the insulation characteristics. For the determination of the moisture behaviour the wettability of the insulator surface is also an important factor. It is the ratio of the interface energies of insulator-water to insulator-air, If this ratio is less than 1, hydrophobicity occurs. A rate for the insulator-water interface energy is the contact angle between water and the surface. The gas permeability is an important factor for solid insulators, if they are intended to be used as gas holder. Fully vitrified ceramics are gas-tight [6].

The resistance to chemical influences is first of all strongly dependent on the material, the concentration, the impact duration and temperature. An insulator is weatherproof if the atmospheric conditions have no influence on its behaviour. It has to resist light, heat, moisture, as well as oxygen and ozone. Also cover sand, salt fog or the corrosive by-products of biological influences like mould and germs are noteworthy [6].

1.3.3 Overview of material characteristics

The positive features and limitations of porcelain are [2, 8]:

+ gas tight
+ high tracking resistance
+ resistive to damage by surface electrical discharge and leakage current activity
+ not sensitive to sunlight and high-energy radiation
+ high heat resistance up to 1000°C
+ good corrosion and ageing resistance
+ meets dynamic requirements
+ good electrical characteristics, even at high temperatures
+ basically a high resistance to chemical influences
+ resistive to hydrochloric acid, nitric acid and sulphuric acid, therefore mostly resistive to atmospheric influences
– sensitive to hydrofluoric acid, phosphate acid, sodium hydroxide
– relatively complex and expensive manufacturing process
– sensitive to overstress
– its brittle nature, making it vulnerable to breakage, chipping and cracking
– not the best dielectric characteristic (less disturbing)
– low tensile and cantilever strength-to-weight ratios
– possibility of cracking and failure by the thermal effects of power arcs

Properties	**Symbol**	**Units**	**Value**
Open (apparat) porisity, max.	p_a	$Vol\%$	0.0
Bulk density, min.	ρ_a	gm^{-3}	$2.5 \cdot 10^6$
Flexural strength, unglazed, min.	σ_{ft}	MPa	140
Flexural strength, glazed, min.	σ_{fg}	MPa	160
Modulus of elasticity, min.	E	GPa	100
Thermal conductivity, 30°C to 100°C	λ_{30-100}	$Wm^{-1}K^{-1}$	1.5 to 4.0
Resistance to thermal shock, min.	ΔT	K	150
Electric strength, min.	E_d	$kVmm^{-1}$	20
Withstand voltage, min.	U	kV	30
Relative Permitivity, 48Hz to 62 Hz	ϵ_r	-	6 to 7.5

Tab. 1: Alkaline alumino-ailicate type porcelain - C130 [10]

1.3.4 Alkaline aluminosilicate - C130

The IEC defined nine groups of ceramics for different material compositions. The focus in this work lies on the group C100, the group of alkaline aluminosilicates, especially in the material composition C130, which was the material of choice for the tested station post insulators. C130 is a non-refractory ceramic with an impressive strength for high-tension insulators. The material characteristics demanded by the IEC are shown in table 1 [9].

1.3.5 Metal fittings

Metallic hardware is used to mount the insulating material to its supporting structure, or mount a stack of insulators to each other. As the fittings hold the entire load, a hardware break is unacceptable. High quality materials have to be used for the long-term mechanical performance. Galvanised, malleable or ductile iron, steel or light alloys are the used materials for fittings of station post insulators. Excessive concentrations of stress should be avoided in the fitting, due to the brittle nature of ceramic. Bitumen paint is applied at both fitting and ceramic material, cement is used as filling material. [2, 11].

1.4 Electrical considerations for insulators

1.4.1 Electrical characteristics

Dielectric strength Is the quotient of the break-down voltage and the smallest thickness of the sample between the electrodes. The break-down voltage is the root mean square value of a

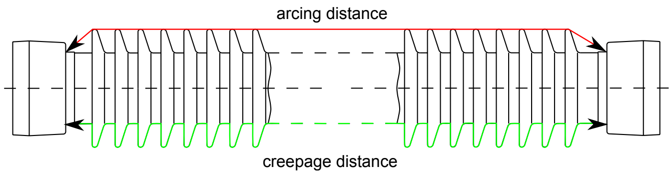


Fig. 7: Arcing distance and creepage distance

sinusoid alternating voltage, at which the puncture or leakage occurs [6].

Dielectric loss factor Is a rate for the energy loss of an insulator, caused by itself in the electric field. It is the tangent of the loss angle, at which the angular phase shift between current and voltage is $\pi/2$, if the dielectric of the capacitor only consists of the insulating material [6].

Measuring the frequency, the temperature dependence of the permittivity and the dielectric loss factor reveals valuable information on the insulator structure. The permittivity of an insulating material is the spare quotient of the propagation speed of the plain electromagnetic wave in vacuum and the insulating material. The permittivity ϵ_r depends primarily on the atomic and molecular properties of the material, the structure and thickness. The dielectric properties of a solid insulator depend on the frequency, the field strength, the temperature, the anisotropy and the humidity [6].

1.4.2 Profile characteristics

Beside the properties of the material, the dimensions of an insulator dictate the electrical and mechanical performance. The arcing distance, the creepage distance and the puncture distance are three fundamental electrical characteristics of dimensioning, affecting an insulators performance.

Puncture distance L_{PD} Is defined as the shortest distance through the insulator between two live parts. To avoid the risk of internal puncture of the solid insulator, which could result in total insulator failure, a sufficient puncture distance is required [12].

According to their design insulators are divided into two classes [13].

- Class A: The puncture distance to arcing distance ratio of the insulator is at least 0.5, such insulators are considered to be unpuncturable. Class A insulators are highly recommended for areas with lightning activity [14].
- Class B: The puncture distance to arcing distance ratio of the insulaotr is less then 0.5, such insulators are considered to be puncturable.

Arcing distance L_{arc} Is defined as the shortest distance in air external to the insulator between two live parts (Fig. 7). For a clean insulator the arcing distance determines the power frequency and impulse flashover voltages. So basically it dictates the physical size of the insulator to meet with the electrical requirements of the system [12].

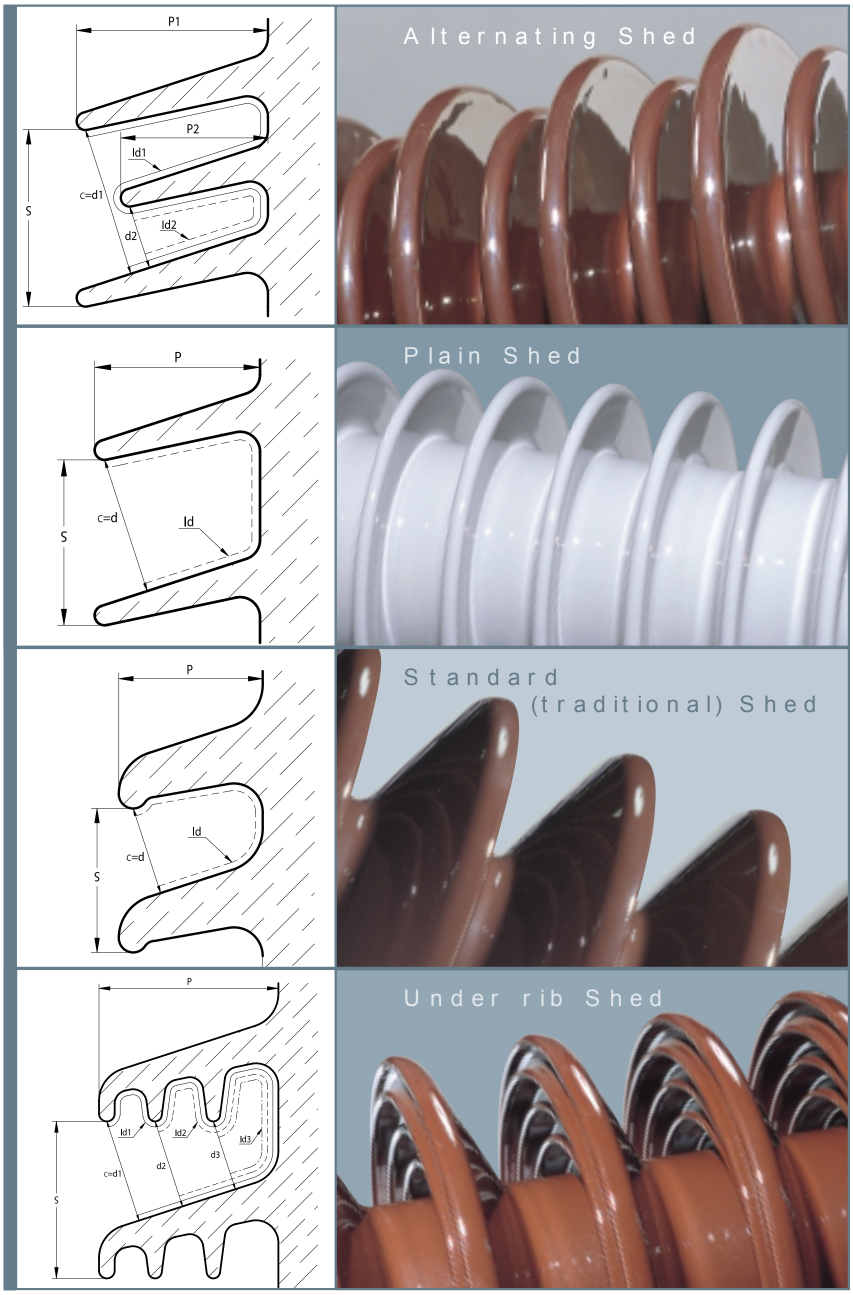
Creepage distance L_{CD} Is defined as the shortest distance on the insulator surface between two live parts (Fig. 7). Otherwise referred to as leakage distance, it is a critical parameter of the power frequency voltage for polluted insulators. The necessary creepage distance to withstand the polluted conditions under system voltage is an often used performance parameter for insulators. It is always intended to use insulators with the shortest overall length but the largest creepage distance as possible. The minimum overall length is determined by the withstand voltage for the air gap (clearance). It is however not a good idea to increase the creepage distance for a constant height indefinitely, because at a certain point the profile loses its efficiency [1, 12].

1.4.3 Shed profiles

To increase the flashover voltage between two conducting parts, insulators feature so called sheds. Sheds are in simple terms a projection from the core of an insulator to obtain an extension of the creepage distance [12]. Actually the shed design is much more complicated. Along with the choice of material, the design of an insulator is the main factor that determines its insulation capabilities. Environmental conditions play an important role for the shed geometry, there are different shed profiles for different applications. Figure 8 shows 4 basic shed profiles for various applications:

- Standard (traditional) shed profile
- Plain shed Profile
- Alternating shed profile
- Under-ribbed shed profile

Standard (traditional) shed profile The standard profile is the most common shed profile used for insulators. It has relatively thick sheds with a small nose at the underside of the shed to increase the creepage distance. This profile is used in areas with "very light" or "medium" pollution where an aerodynamically effective profile and a long creepage distance is not required [12].



c: shed clearance - length of the perpendicular of the lowest point of the shed to the shed below

S: shed spacing - vertical distance between two similar points on successive sheds

P: shed projection - the maximum shed overhang

d: the straight air distance between any two points on the shed surface

l_d: the creepage distance between the two points that define d

l_S: the creepage distance between the two points that define S

Fig. 8: Insulator profile consideration [15]

Plain shed profile The plain shed profile is an enhancement of the standard profile based on better development techniques and stronger mechanical characteristics of the insulation material. This profile combines the demands for an improved F_f and reduced weight by simply removing the small under-rib and reducing the thickness of the sheds. The result is a weight decrease of 15% and an increased F_f by approximately 10% [16].

Alternating shed profile The alternative shed profile has the same shed design as the plain shed design, with the difference of a minimum 30 mm in diameter smaller alternating second shed. It has the benefit of an increased creepage distance without effecting the performance in heavy rain or icing. The longer creepage distance is realized by the greater number of sheds, a smaller clearance and an outer shed with larger diameter. [12].

Under-ribbed shed profile The under-ribbed shed profile is a standard anti-fog profile with a couple of ribs at the underside of the shed. It is used in heavily polluted areas exposed to salt water fog or spray, or other dissolved pollutants with the need of an extra-long creepage distance [12].

1.4.4 Profile factors

As described in figure 8, the ratios S/P, l_d/d, as well as the clearance c are important factors to avoid shed-to-shed arcs. Values recommended by the IEC are given in table 2. The upper shed angle α is responsible for the natural washing of the insulator. The creepage factor and profile factor are also indicators for profile considerations for an insulator.

$$CF = \frac{L_{CD}}{L_{arc}} \tag{1.22}$$

$$PF = \frac{2P + S}{l_S} \quad or \quad \frac{2P_1 + 2P_2 + S}{l_S} \tag{1.23}$$

Shed number An increase of the shed number, while maintaining the same overall length of the insulator, results in an increased creepage distance. However, if the clearance is too little, the flashover frequency increases.

Shed angle Tests for various shed angles have shown that shed angles of more than 30 degrees result in an increase of the flashover frequency. It is caused by protected zones which cannot be reached through natural cleaning [1].

c	$\geq$	$30\ mm$, or $25\ mm$ when $IL \leq 550\ mm$
S/P	$\geq$	0.65 for plain, 0.75 for ribbed
l_d/d	$<$	5
$P_1 - P_2$	$\geq$	$15\ mm$
α	$>$	5° & < 25°
β	$>$	2°
CF	$\leq$	3.5 for SPS Class a to 4 for SPS Class e
PF	$>$	0.8 for light to medium or 0.7 for heavy to very heavy pollution areas

Tab. 2: By IEC 60815-2 recommended profile parameter limits [17]

Diameter Measurements have shown, that an insulator with the same creepage distance but a larger shed diameter and shed distance has a better pollution behaviour then an insulator with a smaller shed diameter and shed distance. Insulators with an alternating shed design have also perform well. Despite having more sheds, the distance between them is large enough [1].

1.4.5 Breakdown behaviour - discharge behaviour

An electrical breakdown means a temporary or permanent loss of the insulation capacity and therefore the insulation can no longer fulfil its basic task. There are three mechanisms responsible for the breakdown:

Pure electric breakdown The breakdown happens without significant heating or stress by partial discharge. The insulator loses its insulation capacity after being stressed for a short period of time (nanoseconds). In a solid insulator a high electrical field strength causes an increase of the electrical conductivity. This happens due to an increase of the free electrons in the conduction band. If the electric field reaches the breakdown field strength, the current density reaches a level, where a disruption of the dielectric is inevitable. [1].

Thermal discharge Insulators have a dielectric loss, which is the sum of the conductive losses, polarization losses and ionisation losses. These losses increase the temperature of the dielectric and are heavily temperature dependent. In the range where the dielectric losses rise strongly with the temperature, the temperature increases vastly, ultimately causing a breakdown. A thermal breakdown appears if a stable operating point cannot be reached because of poor cooling [1].

Partial discharge Partial discharges are breakdowns which only bridge a part of the insulation. They can appear inside the insulator (vacuoles, dielectric or metallic defects) or at the dielectric interfaces. Long-term voltage stress could cause inner partial discharge in the insulator, which could damage the dielectric. Following this damage, effects like heating, erosion, chemical effects or charge carrier injections can be considered [1].

1.4.6 Flashover behaviour

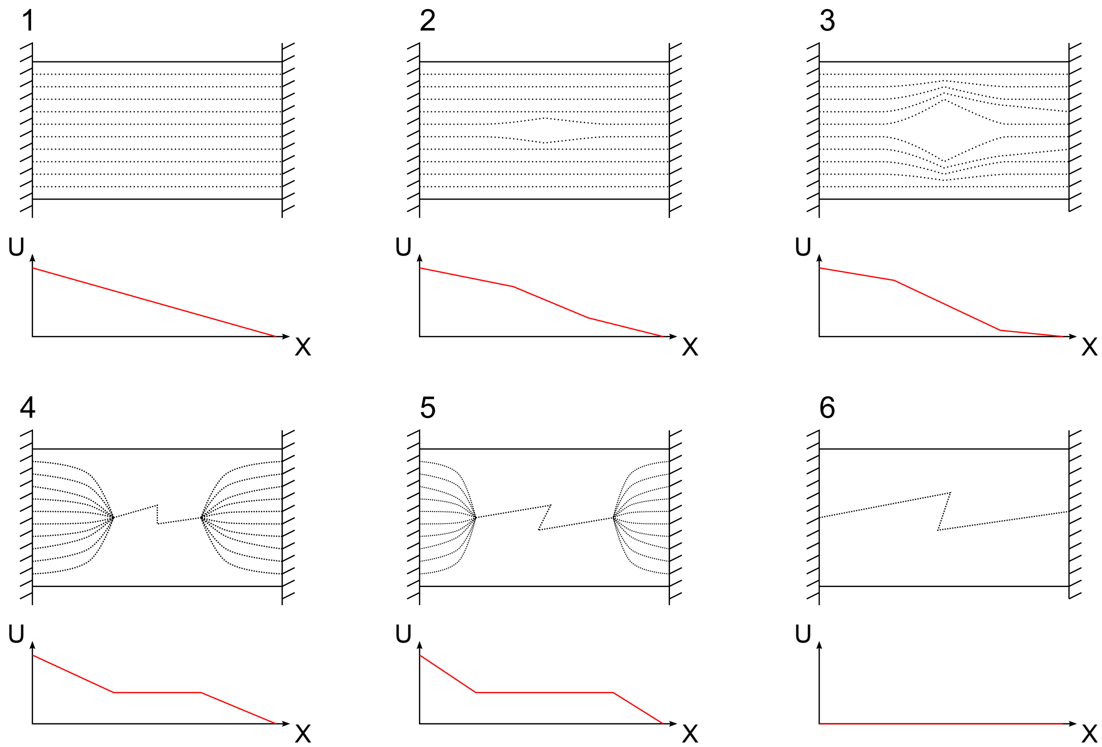
The electric breakdown forms a breakdown channel with a conductive connection between the electrodes across the insulator. A flashover is a special form of an electric breakdown, it has more physical conditions and at least one part of the breakdown distance is at the interface between dielectrics (gaseous/solid, gaseous/liquid, liquid/solid) [11]. In principle there are two forms of flashovers: 1.) Creep flashover (carried gaseous discharge): flashover across clean and dry insulator surfaces, and 2.) Pollution layer flashover: flashover across polluted and wet insulator surfaces

Creep flashover For this form of flashover the characteristics of the gaseous discharge have to be considered. The electrical field lines are vertical to the insulator surface. Normally the discharge develops along the direction of the field lines, but in this case a creep discharge occurs in direction of the insulator surface. Because of the normal field component there is a partial exchange of charge carriers between the solid and the fluid or gaseous insulating materials until the surface charge causes a field compensation. The described carried gaseous discharge has similar characteristics to the gaseous breakdown [1].

Pollution layer flashover Insulators under atmospheric conditions are exposed to surface pollution with metallic or dielectric particles. These particles, combined with dust and moisture, could cause field disturbances and later a reduction of the flashover resistance. At interfaces between solid and gaseous materials various physical mechanisms like condensation and absorption occur. During normal atmospheric conditions solid or wet pollution layers settle on the insulator surface, they can be thin or thick bonded layers. The wind force, as well as the insulator shape, influences the regularity of the spreading and the thickness [1]. Figure 9 shows the different mechanisms for a pollution flashover.

1.4.7 Dry and wet power frequency flashover

An insulator has to withstand the system power frequency operating voltage (U_n) and overvoltages (U_{ov}) under wet and dry conditions. A determining factor for the dry power frequency flashover voltage and to a large degree also for the wet power frequency flashover voltage is the arcing distance [2].



1 A solid and dry insulator should theoretically have a steady conductivity and therefore a linear voltage distribution. In practice the earth capacitance and the field regulation mechanisms are causing a non-linear voltage distribution.
2 A leakage current is causing a heating of the surface and the pollution layer is drying up on some regions. The conductivity decreases in these regions.
3 These regions cause an enhanced current density at the edges, which leads to more drying. The expansion of these dry regions continues.
4 Forming of dry regions is causing an uneven voltage distribution and partial flashovers can occur all over the insulator.
5 An increased current density at the beginning and the end of the partial flashover is causing additional heating. This however causes more drying of the pollution layer and the partial flashover is expanding in the directions of the electrodes.
6 After reaching the electrodes a total flashover occurs.

Fig. 9: Different states of pollution flashover [1, 11]

1.4.8 Lightning and switching impulse flashover

An insulator has to withstand naturally induced lightning and system switching impulse overvoltages without permanent damage. A determining factor for both the dry lightning and wet switching impulse flashover voltage is the arcing distance. The magnitude of a lightning impulse flashover depends mainly on the severity of the lightning and is more dominant at system voltages below 300 kV. Switching impulses correlate to the system voltage and to the time the impulse needs to bridge the air gap. Below 300 kV switching impulses are not critical for flashovers, they don't have enough time to bridge the air gap [2].

1.4.9 Power frequency pollution flashover

The power frequency flashover voltage correlates with the pollution performance of an insulator, it can be reduced if a conducting pollution layer is present on the insulator surface. Pollution layers however have no significant effect on the lightning and switching impulse flashover voltage and are ignored for these conditions [2].

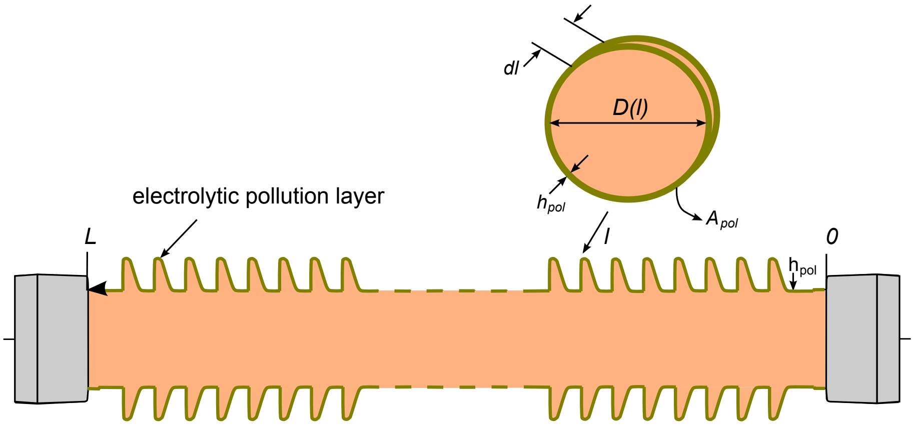
1.4.10 Leakage current amplitude and surface resistance

For a solid insulator between two voltage levels it is very disruptive if a current flows, following a conductive pollution layer. This can even occur for materials with a good insulation level in clean state. The creepage current on this external pollution layer can cause flashovers with different terms of time and location, which could thermally stress the insulator and even disrupt it. The result of such a thermal decomposition is a leakage track, which could cause a short circuit under certain conditions [6].

The electrical insulation resistance describes the resistance between two electrodes. A distinction between the inner and outer electrical insulation resistance should be made. Both can be determined using certain measuring arrangements. However, the influence which the resistances exert on each other can not be eliminated. The outer resistance of an insulator provides information on the current insulating state, which is affected by factors like humidity, mould, precipitation and dust. These informations can only be compared with the volume resistivity, which is the only clearly measurable value. The volume resistivity is the resistivity of a cube with an edge length of 1cm in $\Omega \cdot cm$ [6].

As mentioned, the outer resistance depends on the glaze, the shape of the insulator surface and strongly on outer influences like humidity and pollution. The outer resistance is a function of the material composition and the temperature. An unpleasant factor is the decreasing glaze resistance with increasing temperature. An elevated temperature causes an increased current flow through these regions, causing the insulator to heat up even further, if there is not sufficient natural cooling[8].

The leakage current is one of the main parameters determining an insulator's performance. Statistical and experimental evaluations have shown that the flashover probability increases if the leakage current reaches a certain threshold. It has been defined as the amplitude of the



R_{pol}: surface layer resistance of the electrolytic pollution layer, in $M\Omega$
ρ_{pol}: volume resistivity of the electrolytic pollution layer, in $M\Omega \cdot mm$
LCD: total insulator creepage distance, in mm
A_{pol}: cross-sectional area of the electrolytic pollution layer at position l, in mm^2, as calculated by $A_{pol} = \pi \cdot D(l) \cdot h_{pol}$
$D(l)$: diameter of insulator at position l along the insulator creepage path, in mm
h_{pol}: thickness of the uniform electrolytic pollution layer, in mm

Fig. 10: Visual representation of the electrolytic pollution layer on an insulator [2]

leakage current peak of the half cycle immediately preceding flashover [18].

$$I_{max} = \left(\frac{SCD}{15.32}\right)^2 \tag{1.24}$$

The specific creepage distance SCD is given by:

$$SCD = \frac{LCD}{U_m} \tag{1.25}$$

LCD: total insulator creepage distance, in mm
U_m: maximum phase to phase system voltage, r.m.s., in kV

The insulator's surface layer resistance is strongly affecting the leakage current, it also provides information whether the insulator will flash over or not. Figure 10 shows an example for an insulator with a uniform electrolytic pollution layer. The calculation of the surface layer resistance is as follows [2]:

The basic formula for the resistance R with the volume resistivity ρ, the length of the resistive element l and a cross sectional area A is:

$$R = \frac{\rho \cdot l}{A} \tag{1.26}$$

To apply this formula to the model shown in figure 10, we divide the surface into small sections dl and substitute A_{pol}.

$$R_{pol} = \frac{\rho_{pol}}{h_{pol}} \int_0^L \frac{dl}{\pi \cdot D(l)} \tag{1.27}$$

This formula can be further simplified to 1.28

$$R_{pol} = \frac{F_f}{\sigma_s} \tag{1.28}$$

where:

$$\sigma = \frac{1}{\rho_{pol}} \tag{1.29}$$

$$\sigma_s = \sigma \cdot h_{pol} \tag{1.30}$$

$$F_f = \int_0^L \frac{dl}{\pi \cdot D(l)} \tag{1.31}$$

σ: volume conductivity of the insulator electrolytic pollution layer, in $\mu S/mm$
σ_s: surface conductivity of the insulator electrolytic pollution layer, in μS
F_f: form factor of the insulator

Risk, respectively Holzhausen described the critical flashover voltage for the insulator surface resistance when reaching a critical low value [19]:

$$V_c = k_1 \cdot 10^{-3} \cdot \left(\frac{R_c \cdot 10^6}{LCD}\right)^{k_2} \cdot LCD \tag{1.32}$$

V_c: critical insulator flashover voltage, in kV peak
R_c: critical insulator resistance in $M\Omega$, the critical value R_{pol}
k_1: 7.6
k_2: 0.35

The basic formula for the resistance in 1.26 shows, that the creepage distance is first-hand affecting the insulator surface resistance. By simply increasing the creepage distance it is possible to improve the power frequency pollution flashover performance.

Minimum Specific Creepage Distance (mm/kV)				
Pollution Severity Class		**AC** Calculated using system highest voltage of U_m (phase to phase)	**AC** Calculated using system highest voltage of $U_m/\sqrt{3}$ (phase to ground)	**DC**
a	Very Light	12,7	22	27,5
b	Light	16	28	20
c	Medium	20	35	24
d	Heavy	25	43	31
e	Very Heavy	31	54	38

Tab. 3: Recommended specific creepage distances [12]

The influence of the form factor (1.31) on the surface resistance also demands profile considerations. F_f gives an exact relation between the resistivity/conductivity of a uniformly conductive layer and is only dependent on the shape of the surface and not on the size [12, 20]. There is a study which recommends replacing the creepage distance with the form factor as the standard characteristic, because the form factor gives a better evaluation of the pollution performance [21].

Table 3 shows the recommended specific creepage distances at various pollution severity levels for both AC and DC. IEC 60815 has given these recommendations for insulators with a diameter smaller than 300 mm, for larger diameters an increased specific creepage distance is recommended. For diameters between 300 and 500 mm, an increase of 10%, for diameters of 500 mm and above an increase of 20% is suggested. Also an increased specific creepage distance is required if the insulator is used as phase-to-phase spacer, it should be multiplied by $\sqrt{3}$ [12].

1.4.11 Corona

Where non-uniform fields in high voltage engineering are unavoidable, the phenomenon of partial discharge is of great importance. This discharge is also known as corona discharge and occurs if the electric field strength reaches a specific threshold. The electric field strength is still too low for a spark discharge, but high enough for the ions to work as charge carriers in these highly energized regions, causing a low current between air and the electrodes [22].

Despite the emission of acoustic noise, radio and TV interference, corona discharge could lead to deterioration of (polymeric) insulation by discharged ions and the action of chemical compounds (ozone and, in the presence of moisture, acids), formed by the discharge. To avoid any discharge effects, the corona extinction voltage has to be greater than the system's highest voltage (U_m). If the insulator itself does not fit these requirements, additional hardware has to be used. Corona rings above 200 kV are commonly used for this task [2].

1.5 Environmental factors

Environmental influences

- Weather
- Pollution
- Mechanical stress
- Electrical stress

1.5.1 Weather

The atmospheric pressure, the humidity and the temperature are well documented and standardized factors effecting the insulation performance. We can basically say that rain, fog, wind, ice and snow affect these factors.

Under clean test conditions and a humidity level of more then 50% a monomolecular water layer is formed on the insulator surface and a flashover voltage reduction could follow. This reduction is also dependent on surface shape and quality, as well as the voltage waveform. Connecting water layers on the insulator surface are formed by rain, fog or dew on cool insulators [1].

1.5.2 Pollution

In general, air contains solid as well as dissolved particles, which could sediment onto the insulator surface and become conductive if wetted/moistened. Up to a certain level, a dusty pollution layer has no bad influence on the electric resistance of the insulation distance, as long as it is dry and therefore almost non-conductive. A small amount of humidity is also tolerated, but a combination of both factors results in a conducting layer, which decreases the electric resistivity of the insulator. A certain amount of humidity causes a conductive layer. Without cleaning the insulation capacity is negatively affected and the result is a steadily increasing surface current. At regions with a high current density the water is vaporising and rapidly terminating partial arcs appear. If the resistance of the residual pollution layer is decreasing, the current continues to rise. This leads to a flashover on parts of the insulator and ultimately to a total flashover [1].

A non-uniform pollution layer leads to a lower flashover voltage, due to the shortening of the flashover arc length [23]. The thickness of the pollution layer also has a large influence on the breakdown voltage, because it is responsible for the water absorption of the pollution layer. At worst case, the breakdown-voltage could decrease to a level which is lower than the operating voltage. In other words, the pollution layer flashover voltage rises with decreasing pollution layer current and decreasing surface conductance [1].

Pre-deposited pollution:

Marine:	salt and sand
Industrial:	chemical emissions and waste products
Agricultural:	soil, fertilisers, weed killers and crop burning
Desert:	sand and salt
Other:	salted roads and bird droppings

Instantaneous pollution:

Marine:	salt fog
Industrial:	acid fog
Agricultural:	crop spraying
Desert:	coastal fog
Other:	bird streamers

1.5.3 Mechanical stress

Mechanical stress appears in the different operating conditions in form of dynamical, quasi-stationary or stationary application of force. Inner and outer mechanical stress to the insulator can be distinguished. Outer forces are wind force, ice deposits, earthquakes or the current force at a short circuit. Inner forces depend on manufacturing and appear if heating of the insulator causes an uneven expansion [1].

1.5.4 Electrical stress

1. **Inner overvoltage:** Storage elements in the grid cause voltage transients at switching operations. The insulation has to withstand these temporal events, important are the duration and the voltage elevation factor.
2. **Outer overvoltage:** They originate through energy inputs in the grid in the form of atmospheric discharges.

1.6 Manufacturing procedures of ceramic insulators

For the manufacturing of ceramic post insulators there are two commonly used procedures, the conventional plastic production process for wet-process porcelain and the more advanced isostatic pressure process, both shown in figure 11.

Raw materials The first step in the manufacturing process is the selection of the raw materials. Ceramic for insulators has a basic material composition of 40-50% kaolin, also called china clay, 30-40% quartz and 20-30% feldspar. Kaolin is clay in its purest form, and has a white body after firing. Chemically speaking is it a hydrous aluminium silicate ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$), mixed with water gives it ceramics its plasticity. The second group of materials are the grog and flux material quartz (SiO_2) and feldspar ($K_2O \cdot Al_2O_3 \cdot 6SiO_2$). Quartz has a volume extension of about 18% after firing, it counteracts the dehydrating and shrinking of kaolin. Feldspar is added to the mixture as a flux material to fill the interspace, thicken the ceramic and reduce the porosity. Fired ceramic has a porosity of 2-6%, the pores are however sealed [6, 8, 11].

Milling & mixing Because of the different proportions of the basic materials and a deliberate contamination with synthetic metallic oxides (Al_2O_3,..) there are many possible ceramic compositions with different electrical, mechanical and chemical characteristics. This fact calls for the purity of the raw materials being at a very high level and monitored during the manufacturing process [6].

Quartz, fired scraps and unfired residues of the extrusion and turning processes are put together with water into a mill work to be milled to a size less than $10\mu m$. The clays need more energy to disperse them in water and so they are put into a blunger, a octagonal tank equipment with rotating blades. The blended components are mixed on the basis of density measurements of their dry weight. Still remaining ferromagnetic impurities in this liquid mixture are extracted in filter screens and magnetic separators [11].

Plastic production process The mixture of the raw ingredients is put into a filter press to remove the major amount of the water. After this procedure the water content is at a level of about 30%, to accelerate this process sometimes heat is applied to reduce the viscosity. Subsequently the mass is pre-extruded into smaller blocks and stored for a couple of days to homogenize the material. The next shaping step is a second extrusion. This time the blocks have the final size and are plugged either into solid or hollow cylinders. The raw blocks are stored again for drying to a humidity level of about 20%. The drying process is a combination of circulating warm air and resistive heating by applying an alternating current to the body [11].

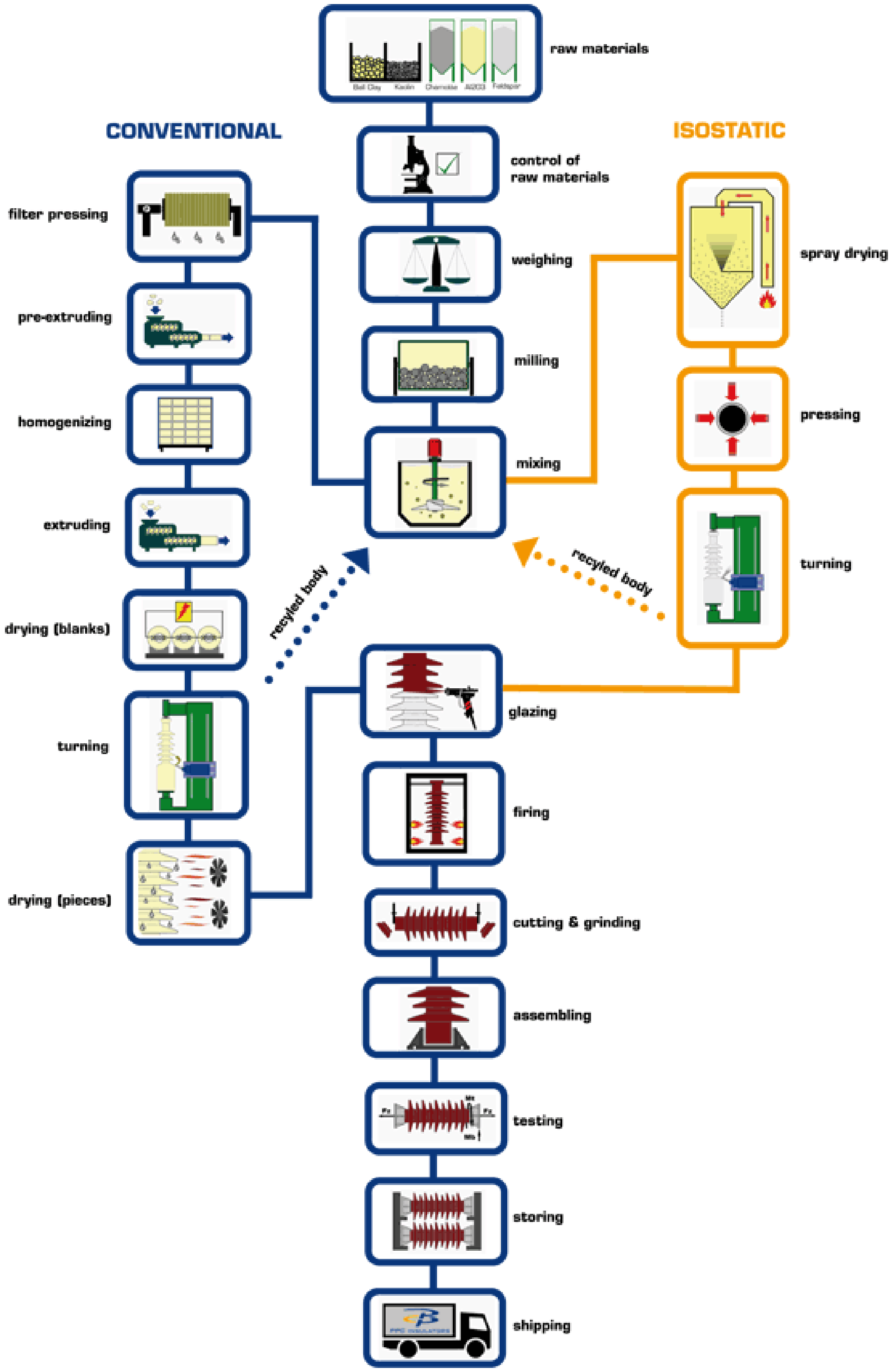


Fig. 11: Conventional and isostatic manufacturing process of porcelain insulators [24]

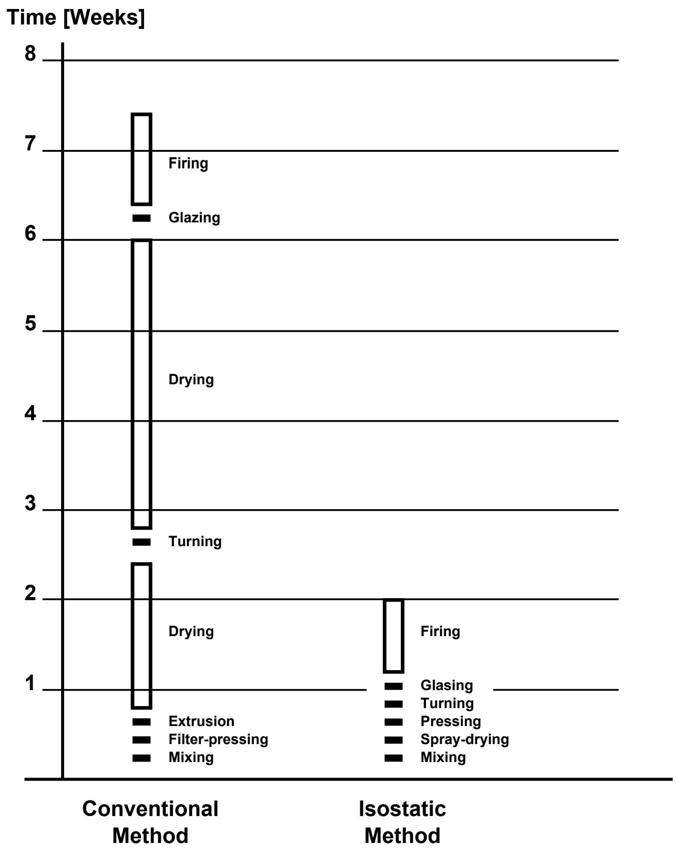


Fig. 12: Comparison between production time of isostatic pressing and plastic method [25]

Bringing the insulator to its final shape is performed on turning lathes. Despite the softness of the ceramic at this stage, the material is very abrasive. Special carbide-tipped tools are necessary to avoid loss of precision. Removal of the material is also a sensitive matter, as removing it too quickly could cause internal damage [11].

The next production step is the final drying before glazing and firing, the humidity level of 20% has to be reduced to 1-2%. This step takes up to 3 weeks and is managed with resistive heating by applying alternating current. An alternative or additional method is dehumidifying the ambient air. An improper final drying causes a non-uniform humidity level inside the body which later can lead to problems in the kiln or later cause errors during mechanical testing [11].

Glazing Basically all ceramic outdoor insulators are glazed, the purpose is to smooth the surface for minimizing the specific surface area and reducing catch of dirt. Glazes are basically mobile crystals out of silica and other oxides with other compounds. Glazes don't act despite some believes as a water seal, all electrical porcelains are fully vitrified and impermeable to moisture. If an insulator is under compression, glazes are supposed to increase the mechanical strength. To do so the expansion coefficient of the glaze has to be lower than that of the ceramic, this is realized with the material composition of the glaze [8].

The glaze raw materials, feldspar, china stone, quartz, clays, bentonite, alkaline earths are mixed together with 1-2% water. During the firing process the glazes fill the imperfections on the insulator surface and reduce the porosity. The water is soaked into the insulator surface leaving a uniform coating (high-firing glaze). By neutralizing the notch effect the sherds get strengthened at these positions [11].

The glaze usually is coloured white, green or brown. The darker the color the more heat can be absorbed and the insulator dries faster if wetted [6]. To improve the flashover voltage under wet conditions there is a treatment method for glazed porcelain insulators [26], alternatively the insulator can also be coated with silicone rubber [27].

Firing During the firing process chemically bonded water is the first element which is released from kaolin. Then, the other elements soften in order of their respective melting points. Feldspar melts first and, combined with clay (dehydrated kaolin $Al_2O_3 \cdot 2SiO_2$), forms mullite ($3Al_2O_3 \cdot 2SiO_2$), which dissolves a part of the quartz. At the sintering point at between 1200°C and 1500°C (depending on the mixing proportion of the raw materials) the entire mass is softened [6, 8].

During the following cooling process the components shrink varyingly, according to their expansion coefficient and tension is built inside the insulator. As long as the molten mass of feldspar is still soft, this tension can be neutralized. At the transformation point at approximately 850°C the whole mass is solidified and again inner tension is built. This tension is supposed to improve the strength, but is critical to the mechanical stress. After the firing process the insulator shrank between 10% and 20%, depending on the material composition and the insulator design. The firing process is less sensitive if the firing interval (temperature range between transformation point and sintering point) is higher [8].

Assembling After the firing process the insulators are grinded and cut to their final length. After the assembly of the armatures the production process of the insulators is finished and the insulators are ready for quality control and shipping. The test procedures are discussed at a later point of this thesis. Almost all by-products of the manufacturing process are recycled and put back into the mill work.

Isostatic processing The first steps of the plastic production process and the isostatic pressing process are the same, the difference starts after mixing. In the plastic production process the mixture is put into a filter press, in the isostatic pressing process the liquid goes to a spray dryer. The result is a fine ceramic powder with a humidity ratio of less than 1% [21, 25].

The powder is fed into a moulding bag, commonly polyurethane, inside an isostatic press. The press is sealed and at room temperature the isostatic pressure is increased to a value between 20 MPa and 280 MPa, pressing the powder down to 50% of its initial volume. The powder compacts and forms a solid block in the shape of the moulding bag. To avoid cracks due to rapid gas expansion the pressure is released slowly [25, 28, 29].

Right away, the next production step is right away the shaping of the raw forms, without waiting for the material to dry, as in the conventional production process. Therefore the block is put into a turning lathe and the excess material is removed with a cutting chisel. The following steps of the manufacturing process are the same as in the plastic production process and will not be discussed again at this point [28, 30].

The advantages of the isostatic pressing compared to the plastic process are [25]:

- a faster manufacturing process (2 weeks instead of 7 to 8 weeks) (fig. 12)
- a better uniformity of the shape
- more dense and homogeneous material composition
- more complex production shapes possible
- no impurities on the surface due to sedimentation during drying
- larger core diameters possible, only limited by the press chamber

2 Relevant Standards

2.1 Summary

For the selection of Ceramic Solid-Core Station Post Insulators for UHVAC Outdoor Applications the following standards are relevant:

Relevant European Standards:

- IEC 60273 - Characteristic of indoor and outdoor post insulators for systems with nominal voltages greater than 1000 V
- IEC/TS 60815-1,2 - Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 1: Definitions, information and general principles, Part 2: Ceramic and glass insulators for a.c. systems
- IEC 60168 - Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1000 V
- IEC 60437 - Radio interference test on high-voltage insulators
- IEC 60507 - Artificial pollution tests on high-voltage insulators to be used on a.c. systems
- IEC 60672-1,2,3 - Ceramic and glass insulating materials - Part 1: Definitions and classification, Part 2: Methods of test, Part 3: Specifications for individual materials
- IEC 60060-1,2,3 - High-voltage test techniques - Part 1: General definitions and test requirements, Part 2: Measuring systems, Part 3: Definitions and requirements for on-site testing
- IEC 60071-1,1-am1,2 - Insulation co-ordination - Part 1: Definitions, principles and rules, Amendment 1 - Part 1: Definitions, principles and rules, Part 2: Application guide

Relevant US Standards:

- ANSI C29.1-1988(R2002) - Test Methods for Electrical Power Insulators
- ANSI C29.9-1983(R2002) - Wet Process Porcelain Insulators (Apparatus, Post Type)
- ANSI/IEEE Std 4-1978 - IEEE Standard Techniques for High-Voltage Testing

2.2 IEC 60273 - Characteristic of indoor and outdoor post insulators for systems with nominal voltages greater than 1000 V [31]

IEC 60273 applies to post insulators with a nominal voltage greater than 1000 V and a frequency up to 100 Hz. This standard provides standard values for electrical characteristics, mechanical characteristics and dimensions for five defined types of post insulators. The focus in my investigation was on outdoor cylindrical post insulators of ceramic material with external metal fittings. The IEC specified notation for this insulator type is as followed:

IEC post insulator Type $\underbrace{C}_{\text{I}}\underbrace{8}_{\text{II}} - \underbrace{1300}_{\text{III}} - \underbrace{I}_{\text{IV}}$

I) C stands for the assigned reference symbol for outdoor cylindrical post insulators of ceramic material or glass and with external metal fittings

II) 8 is the mechanical strength class and means the insulator has a specified failing load of 8000 N, defined classes are 2 - 4 - 6 - 8- 10 - 12,5 - 16 - 20 - 25 - 31,5 and 40

III) 1300 is the specified lightning impulse withstand voltage in kV, in IEC 71-1 defined values are 60 to 2550.

IV) I is the creepage distance class, values are I and II

Post insulator designation	Lightning impulse withstand voltage	Switching impulse withstand voltage	Power-frequency withstand voltage, wet	Height of post insulator	Minimum nominal creepage distance		Failing load
					Class I	Class II	Bending
	kV	kV	kV	mm	mm	mm	N
C8-1300	1300	950	-	2900 ± 4,5	5100	7000	8000
C8-1425	1425	950	-	3150 ± 4,5	5600	7800	8000
C20-1425	1425	950	-	3150 ± 4,5	5600	7800	20000
C20-2100	2100	1300	-	4700 ± 5,5	8250	12250	20000
C8-2550	2550	1550	-	5700 ± 6,5	9800	15000	8000
C12,5-2550	2550	1550	-	5700 ± 6,5	9800	15000	12500

Tab. 4: Required IEC Classifications for used Post Insulator Type C [31]

Dimensional characteristics specified in this standard are the overall height, the maximum nominal diameter of the insulating part, fixing arrangements, tolerances and the minimum nominal creepage distance. However, the composition (number, size, positioning of the insulator units) of the post insulator is not specified. Table 4 shows an extract of the standard with relevant data used for this investigation. As there is no reference in the standard for insulators with a impulse withstand voltage of 2050 kV so the next value was used.

2.3 IEC/TS 60815 - Selection and dimensioning of high-voltage insulators for the use in polluted conditions [12, 17]

IEC/TS 60815 is a three-part technical specification, Part 1 and Part 2 are relevant for this investigation. Part 3 is for polymer insulators for a.c. systems. IEC/TS 60815-1 recommends three approaches for the selection and dimensioning of suitable outdoor insulators for polluted conditions out of catalogue. Which approach to choose depends, based on system requirements and environmental conditions, on the available data, time and economics. The reliability of each approach depends strongly on the decisions taken during the selection process. The effects of snow, ice or altitude on polluted insulators haven‘t been considered in this technical specification.

2.3.1 Input parameters

The selection and dimensioning of outdoor insulators is a complex procedure and in order to obtain a reliable result, a wide range of parameters have to be considered. The input parameters are categorized in three major groups: system requirements, environmental conditions of the site and insulator parameters from manufacturer's catalogues. Table 5 shows a brief overview of the input parameters for the selection and dimensioning of insulators, all parameters are discussed in depth later.

System requirements	**Enviromental conditions**	**Insulator parameters**
- Type of system - Maximum operating voltage across the insulator - Insulation co-ordination parameters - Imposed performance requirements - Clearances, imposed geometry, dimensions - Live line working and maintenance practice	- Pollution types and levels - Rain, fog, dew, snow and ice - Wind, storms - Temperature, humidity - Altitude - Lightning, earthquakes - Biological growths - Vandalism, animals	- Overall length - Type - Material - Profile - Creepage distance - Diameter - Mechanical design - Electrical design - Arcing distance

Tab. 5: Input parameters for insulator selection and dimensioning [12]

2.3.2 System requirements

Type of system (a.c. or d.c.) It is a known fact that the required unified specific creepage distance could vary for a.c. and d.c. insulators for the same pollution conditions. D.c. systems have a slightly higher USCD and therefore comparing both systems is invalid. This thesis focusses on a.c. systems and their according standards and technical specifications.

Maximum operating voltage across the insulation The highest voltage for equipment U_m (the phase-to-phase voltage across the insulation) usually is the determining factor for a.c. systems. The phase-to-earth insulation is stressed with the phase-to-earth voltage $U_{ph-e} = U_m/\sqrt{3}$.

Overvoltage Due to their short duration the influence of transient over-voltages can be ignored. The effect of temporary over-voltages (TOV), caused by e.g. sudden load release of generators and lines, in combination with insulator pollution on the other hand may have to be considered.

Imposed performance requirements They could become the determining factor for the insulator selection. The required performance values are considered with regard to availability, maintainability and reliability.

Clearances, imposed geometry and dimensions These requirements are generally standardized, but there could be cases (e.g. unusual position of an insulator; lines or substations with a low visual impact) where alternative solutions for insulation types and dimensions are required. For my investigation this point is a major issue, as I want to show, that the tested insulator, with an unusually lower height, is reliable for the selected switching impulse withstand voltage.

2.3.3 Environmental conditions

Identification of types of pollution The insulator pollution, which can lead to flashovers, can basically be categorized in two types:

Type A: The pollution is deposited on the insulator surface as a solid layer and has two main components, a soluble pollution which becomes conductive when wetted, and a non-soluble pollution which binds the soluble pollution in form of a layer. ESDD/NSDD and DDGI-S/DDGI-N measurements characterize this type of pollution best. Type A pollution most often occurs in inland, deserts or industrially polluted areas. A dry salt layer wetted by dew, mist, fog or drizzle forms such a pollution.

Type B: The pollution is deposited on the insulator surface as a layer of liquid electrolytes with very little or no non-soluble components. Conductance or leakage current measurements are used to characterize this type of pollution. Type B pollution often occurs in coastal regions as a layer of salt water or conductive fog. Crop spraying, chemical mists and acid rain are other pollution sources.

General types of environments Environments are categorized in five major types. These types basically describe the encountered pollution of a region. Combinations of these types can also occur, in this case the dominant type has to be identified.

"Desert" type environments - Sandy soils, dry periods and salty pollution layers with high NSDD levels describe these areas of mainly wind borne pollution best (type A). Because of the infrequent rain, natural cleaning shows itself to be less efficient. Relatively frequently, the insulator can be critically wetted in form of dew, which can lead to an insulator flashover.

"Coastal" type environments - These areas are typically near coastal regions, the pollution is mainly transmitted onto the insulator surface by wind, spray and fog and can build type A and type B pollution. Type A pollution typically occurs in form of fast dissolving salts that are deposited onto the insulator surface by wind over a longer period of time. Type B pollution forms relatively rapidly during spray or conductive fog conditions. Because of the rapidly dissolving pollution layer natural cleaning shows itself to be typically effective.

"Industrial" type environments - These areas are dominated by industrial pollution sources and both type A and B pollution can occur. Slowly dissolving elements, like cement or gypsum, form type A pollution. The elements of the conductive particles of Type B pollution are metallic deposits, dissolved gasses like NOx, SOx, or coal. The efficiency of natural cleaning strongly depends on the pollution source.

"Agricultural" type environments - These are regions with agricultural activity and the pollution can again be type A and B. The pollution is mainly transmitted by wind during ploughing (salty soils - type A) and crop spraying (fast or slow dissolving salts of chemicals - type B). Natural cleaning depends on the severity of the pollution and the type of the salt deposit but it is mostly quite effective.

"Inland" type environments - These areas have a low level of pollution with an unclear source.

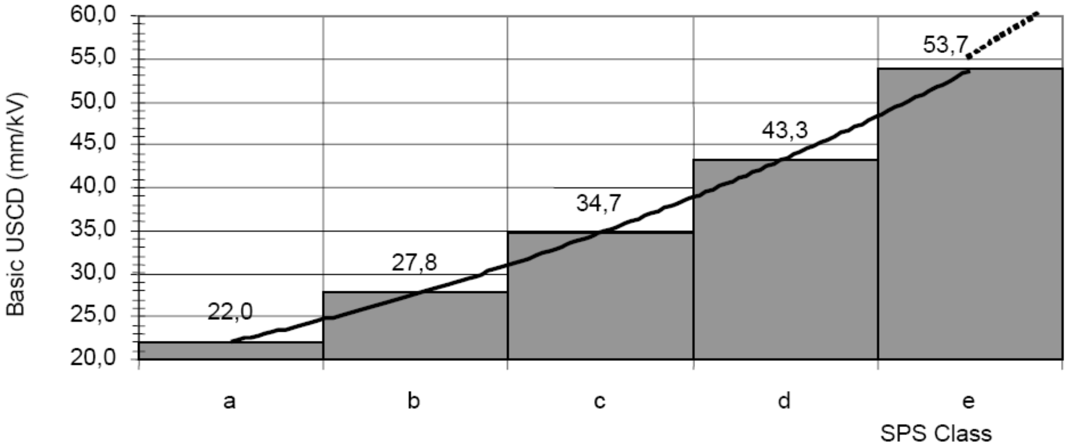


Fig. 13: RUSCD as a function of SPS class [17]

2.3.4 Evaluation of site pollution severity (SPS)

Site pollution severity The site pollution severity is the maximum value of either ESDD/NSDD, SES or DDGI-S/DDGI-N recorded over at least one year to consider possible seasonal pollution events related to the local climate and environmental conditions. The measurement intervals vary from every month to every year and they have to be repeated if rain occurs during the measurements to evaluate the effect of natural washing.

Site pollution severity (SPS) classes Five classes of pollution, from very light to very heavy pollution, have been defined to categorize the site pollution severity (see table 3). It is important to know, that the change from one class to another is gradual and not abrupt. In fact, it is better to consider the actual SPS value for determining the insulator dimensions than the SPS class. Nevertheless, this thesis focusses on class d - heavy polluted insulators.

2.3.5 Reference unified specific creepage distance (RUSCD)

This technical specification is used to determine the reference unified specific creepage distance (RUSCD) from site pollution severity (SPS) class and evaluate the suitability of different insulator profiles. Definitions and recommendations of this technical specification are shown in figure 8 and table 2. The reference unified specific creepage distance (RUSCD) is the creepage distance of an insulator divided by the r.m.s. value of the highest voltage across the insulator, but uncorrected for size and profile. Figure 13 shows the relationship between RUSCD and SPS class.

$$NCD(min) = RUSCD \cdot K_a \cdot K_{ad} \cdot U_{m(phase-to-phase)} \tag{2.1}$$

The required minimum nominal creepage distance $NCD(min)$ is the reference unified specific creepage distance RUSCD multiplied with the correction factor for altitude K_a, the correction factor for insulator diameter K_{ad}, as well as the system maximum phase-to-earth voltage $U_{m(phase-to-phase)}$.

The results of this selection process have to be confirmed. The test methods described in IEC 60507 are used for this purpose. The solid layer test is recommended for type A pollution, the salt-fog test for type B pollution. If the insulator passes the test at the required or a higher pollution severity, the insulator is sufficiently dimensioned.

2.4 IEC 60168 - Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1000 V [32]

IEC 60168 specifies test methods and acceptance criteria to verify the electrical and mechanical characteristics of post insulators. This standard covers six insulator designs and three insulating materials. We focus on ceramic solid-core cylindrical post insulators with external metal fittings for which following characteristics have to be specified:

- specified dry lightning-impulse withstand voltage
- specified wet switching-impulse withstand voltage
- specified wet power-frequency withstand voltage
- specified mechanical failing load
- specified significant dimensions, including the creepage distance
- deflection under bending load (optional)
- radio interference characteristics (optional)
- artificial pollution withstand characteristics (optional)

2.4.1 Test procedures

Until an insulator can be used in the field it has to pass a series of tests. These tests are divided into three groups:

Routine tests Routine tests are carried out on every insulator during the manufacturing process. For ceramic solid-core post insulators with external metal fittings these tests are routine visual inspection and bending tests for insulators with a height $> 770\ mm$ to eliminate defective units.

Sample tests Sample tests are carried out during the manufacturing process on a random sample of insulators to verify the characteristics of an insulator. For ceramic solid-core post insulators with external metal fittings these tests are:

- Verification of the dimensions (arcing distance, nominal core diameter, nominal shed spacing, nominal shed projection, shed profile)
- Temperature cycle test
- Mechanical failing load test
- Porosity test
- Galvanizing test

Type tests Type Tests are carried out on insulators with a new or major change of design or manufacturing process to verify the previously mentioned main characteristics of an insulator. The test is carried out on one post insulator only, which has passed the routine and sample tests, except the sample mechanical test. For ceramic solid-core post insulators with external metal fittings these tests are:

- Dry lightning impulse withstand voltage test
- Wet switching impulse withstand voltage test ($U_m > 245\ kV$)
- Wet power-frequency wistand voltage test
- Mechanical failing load test (tensile test, torsion test, compression test)
- Test for deflection under load (optional)
- Radio interference test (optional)
- Artifical pollution test (optional)

This thesis focusses on the test procedures for electrical tests, the tests and requirements for the mechanical characteristics of a post insulator are secondary for this work.

Overall height (h) of post insulator *mm*	**Height (h) above ground of the mounting surface of the metal support** *mm*
$h \leq 2500$	2500
$2500 < h \leq 3200$	3000
$3200 < h \leq 4200$	4000
$h > 4200$	5000

Tab. 6: Mounting height of outdoor post insulator [32]

2.4.2 General requirements

General requirements for high-voltage tests are in accordance with IEC 60060-1. The atmospheric conditions have to be measured and if they vary from the standard values a correction factor has to be applied. To avoid condensation the insulator should be in thermal equilibrium with the ambient temperature before starting the test. The surface of the insulator should be wiped clean and dry to avoid errors in measurement due to possible surface current. There should be sufficient time between tests to avoid influences from the previous application of voltage in flashover or withstand tests.

2.4.3 Dry lightning impulse withstand voltage test

For the dry lightning impulse withstand voltage tests the withstand voltage procedure with 15 impulses or the more informative 50% flashover voltage procedure are used. For the test the insulator is mounted on a metal support, with a preferably square base plate about equal or twice the size of the bottom fitting and a length according to table 6. The test voltage is applied at one end of a horizontal, cylindrical conductor, mounted to the top fitting, with a length of at least 1.50 times the height of the insulator and a diameter of about 1.5% and 2% of the height of the insulator. The other end of the conductor should be protected by suitable devices to avoid sparkover. The insulator passes the withstand voltage procedure if not more than two flashovers occur. For the 50% flashover voltage procedure the insulator passes if the 50% lightning-impulse flashover voltage is not less than $(1/(1-1.3\cdot\sigma)) = 1.040$ times the specified lightning-impulse withstand voltage. The post insulator is tested with 1.2/50 μs impulses of both positive and negative polarity. If the polarity with the lower flashover voltage is known it is sufficient to test with that polarity.

2.4.4 Wet switching impulse withstand voltage test

For the wet switching impulse withstand voltage tests the withstand voltage procedure with 15 impulses or the 50% flashover voltage procedure are used. The test arrangement is the same as for the dry lightning impulse withstand voltage test. The insulator passes the withstand voltage procedure if not more than two flashovers occur. For the 50% flashover voltage procedure the insulator passes if the 50% switching-impulse flashover voltage is not less than $(1/(1-1.3\cdot\sigma)) = 1.085)$ times the specified switching-impulse withstand voltage. The post insulator is tested with 250/2500 μs impulses of both positive and negative polarity. If the polarity with the lower flashover voltage is known it is sufficient to test with that polarity.

2.4.5 Wet power-frequency withstand voltage test

The wet power-frequency withstand voltage test is carried out according to IEC 60060-1. For the test the insulator is mounted on a metal support, with a base plate about equal the size of the bottom fitting and a length of equal or twice the size of the post insulator. For insulators higher than 1.80 m the distance above ground should be at least 2.50 m. The test voltage is applied at one end of a horizontal, cylindrical conductor, mounted to the top fitting, with a length of at least 1.50 times the height of the insulator and a diameter of about 1.5% of the height of the insulator. The post insulator passes the test if no flashover or puncture occurs during the test. If flashover occurs on the tested insulator, it is allowed to test for a second time, after verifying the rain conditions.

2.5 IEC 60437 - Radio interference test on high-voltage insulators [33]

Radio interference voltage tests have to be carried out according to this standard. The test procedures are only intended to be used in a laboratory on clean and dry insulators and primarily at a frequency of (0.5 ± 0.05) MHz or (1 ± 0.1) MHz or, alternatively, at other frequencies between 0.5 MHz and 2 MHz.

The atmospheric conditions for radio interference measurements deviate from the standard conditions according to IEC 60060-1, normally used for post insulators. Tests have to be performed at a temperature of 10°C and 35°C, at a pressure of 87 kPa and 107 kPa and at a relative humidity of 45% and 75%. During the test the atmospheric conditions have to be recorded and the test voltage and the radio interference measurements stay uncorrected to standard atmospheric conditions. To avoid condensation during the test, the test object has to adapt to the atmospheric conditions in the test area first. Furthermore the test object should be wiped clean from dust or other dirt, that might be affecting the surface.

The test area for insulators should preferably be a screened room, which is large enough not to affect the electric field of the test object. If there is no screened room available the background noise level of the test area should have a sufficiently high signal to noise ratio.

The insulator itself is not the only factor influencing the test result. Also the method of mounting, including the use of arcing horns, grading rings, conductor bundles and their arrangement relative to the insulator have an affect. Any discharge from the high-voltage conductor assembly should be avoided, proper corona-free terminations should protect the end of the assembly. IEC 60168 regulates all the mounting methods used for post insulators.

In the type test, the number of insulators to be tested has to match the number specified for the electrical type test. For post insulators with a height H $\leq 600\ mm$ this number is 3, for post insulators with a height H $> 600\ mm$ it is 1. The RI characteristic determined by calculating the mean value of the test results.

The test procedure for type tests starts at a voltage 10% higher than the specified test voltage and has to be maintained for at least 5 minutes. The voltage will now be decreased to 30% of the specified test voltage, raised again to the initial value, maintained there for 1 min and finally decreased again to 30% of the test voltage. Each voltage change should be carried out in 10% steps of the specified test voltage and at each step measurements have to be made. The RI characteristic of the insulator is obtained by plotting the applied voltage against the measuring points of the last decreasing run. The insulator passes the test if the RI levels don't exceed the specified values of the test voltage.

The test report has to contain the following parts:

- Name of manufacturer
- type designation or description of insulator tested
- details of test arrangements including dimensions
- atmospheric conditions prevailing during the test (temperature, pressure, relative humidity)
- RI characteristics of insulator tested

2.6 IEC 60507 - Artificial pollution tests on high-voltage insulators to be used on a.c. systems [20]

Outdoor ceramic post insulators are not commonly used in clean and dry conditions, therefore the power frequency withstand characteristics have to be determined. IEC 60507 acts as a standard for a.c. systems from 1000 V up to 765 kV under polluted atmospheric conditions. This standard requires two mandatory procedures for artificial pollution tests: the salt fog method in which the insulator is placed into a defined ambient pollution and the solid layer method in which a defined solid pollution layer is deposited on the insulator surface.

Arrangement of insulator For comparison of different insulator types the insulator should be in a vertical position during the test, exceptions are made if the service position is different, or the manufacturer and the purchaser agree to it.

The insulator should have a minimum clearance of 0.5 m per 100 kV or at least 1.5 m to any earthed object other than the supporting structure of the insulator or the columns of the nozzles. The supporting structure and the energized metal parts should reproduce the configurations expected in service.

The influence of capacitive effects of fittings are considered to be insignificant on the test results for test voltages up to 450 kV. A high self-capacitance can have an effect on the external surface behaviour.

General requirements Any trace of dirt and grease have to be removed thoroughly from the insulator with water, preferably 50°C hot, mixed with a detergent (e.g. trisodium phosphate). After cleaning and before every subsequent test the insulator has to be washed with tap water, to remove all traces of pollution again.

The test voltage usually matches the highest phase-to-earth value of the voltage the insulator has to withstand under normal operating conditions, it equates to $U_m/\sqrt{3}$ (U_m: highest voltage for equipment (IEC 71-1)). When testing phase-to-phase or isolated neutral systems the test voltage is higher. The frequency of the test voltage should be between 48 Hz and 62 Hz.

Minimum short-circuit current For artificial pollution tests, the testing plant has to meet three major requirements. The resistance/reactants ratio (R/X) should be equal to or higher than 0.1. The capacitive current/short-circuit current ratio (I_C/I_{SC}) should be between 0.001 and 0.1. And most of all the testing plant requires a minimum short-circuit current (I_{SC}) of $6A$ or higher, which varies with the test conditions. Table 7 describes the minimum value of I_{SC} in

Specific creepage distance mm/kV	**minimum short-circuit current** $I_{SC(rms)}$
$L_S < 16$	$I_{SCmin} = 6$
$16 \leq L_S \leq 25$	$I_{SCmin} = \lvert L_S \rvert$ - 10

Tab. 7: Minimum short-circuit current [20]

Specific creepage distance mm/kV	I_{hmax} A_{peak}
16	0.55
20	0.85
25	1.35

Tab. 8: Leakage current pulse amplitude [20]

relation to the specific creepage distance SCD.

If the minimum short-circuit current (I_{SC}) does not comply with the values demanded in table 7, artificial pollution tests are still valid if the minimum short-circuit current is at least 6 A and the highest leakage current pulse amplitude (I_{hmax}) of all tests complies with table 8.

2.6.1 Salt fog method

The salt solution, which is used for the salt fog method, is made of commercial sodium chloride (NaCl) and tap water and should have a temperature between 5°C and 30°C. The salinity of the salt solution is given by the standard and it has a prescribed tolerance error of ± 5%. The conductivity and density values have to be corrected according to 2.2 and 2.3 if the solution temperature is not at 20°C.

Conductivity correction

$$\sigma_{20} = \sigma_\theta \left[1 - b\left(\theta - 20\right)\right] \tag{2.2}$$

where:

θ	solution temperature (°C)
σ_θ	volume conductivity at a temperature of θ °C (S/m)
σ_{20}	volume conductivity at a temperature of 20 °C (S/m)
b	temperature θ dependent factor

density correction (only valid for salinities over $20 kg/m^3$):

$$\Delta_{20} = \Delta_\theta \left[1 + (200 + 1.3 S_a)(\theta - 20) \cdot 10^{-6}\right] \tag{2.3}$$

θ	solution temperature (°C)
Δ_θ	density at a temperature of θ °C (kg/m^3)
Δ_{20}	density at a temperature of 20 °C (kg/m^3)
S_a	salinity (kg/m^3)

Spraying system The salt fog is produced in a spraying system where the salt solution with a flow of 0.5 dm^3/min at each spray is vaporised by compressed air with a relative pressure of 700 $kPa \pm 35$ kPa and thereby deposited onto the insulator. Two spray columns are placed in parallel, on opposite sides of the insulator in an distance of 3 m. Each spray system is an alignment of sprays spaced at 0.6 m intervals facing toward the insulator. The mid-point of the spray columns should be in line with the mid-point of the insulator and the sprays should extend beyond both ends of the insulator by at least 0.6 m.

Before starting the test The ambient temperature during the test should be between 5°C and 40°C and the insulator should be in thermal equilibrium with the air. Nevertheless the test has to start after cleaning, when the insulator is still completely wet. The temperature of the salt solution should not deviate from the air temperature by more than 15°C.

Test procedure First the insulator is energized. The test starts when the air-salt-solution mixture reaches its operating pressure. The insulator stays energized at the test voltage for 20 minutes, then the voltage is raised every 5 minutes in steps of 10% of its initial value. If no flashover occurs the test ends after 60 minutes. After every complete test cycle the insulator should be washed thoroughly with tap water and the withstand test should start again as soon as possible, if no effects of the previous test are expected.

If a flashover occurs, a voltage with the 90% value of the previously obtained flashover voltage is reapplied as quickly as possible and raised every 5 minutes in steps of 5% of its initial value until a flashover occurs. Then the insulator should be washed and prepared for repeating this procedure a total of eight times.

The insulator complies with the specifications if no flashover occurs within a series of three subsequent tests. If one flashover occurs, the insulator passes the specifications, if a fourth test is completed successfully without flashover.

2.6.2 Solid layer methods

Composition of the contaminating suspension For the contaminating suspension two compositions are described in IEC 60507. One is a Kieselguhr composition, the other is a Kaolin (or Tonoko) composition. To perform the test for a certain degree of pollution on the insulator (allowed tolerance of $\mp$ 15%), the volume conductivity of the prepared suspension has to be determined. Therefore preliminary contamination trials are performed on the insulator, with guidance of the tables in IEC 60507.

Application of the pollution layer The pollution layer is either applied by spraying or flowing on the dry and cleaned insulator, or the insulator is alternatively dipped in the suspension. Before the insulator can be tested the pollution layer has to be dry, aimed naturally or artificially by using hot air.

Degree of pollution of the tested insulator The degree of pollution of the tested insulator is calculated during its wetting by repeatedly measuring the layer conductance and multiplying the value by the insulators form factor. The test voltage applied to the insulator has to be at least 700 Vr.m.s. per metre of the overall creepage distance. To avoid error due to heating or drying of the pollution layer the test voltage should not be much higher and only applied long enough to measure the current flowing through the wet layer.

Withstand test In order to test the flashover voltage two procedures are used. For the first procedure, the polluted insulator is placed in a test chamber with an ambient temperature of ± 2°C of its own temperature. A fog generator is continuously blowing fog around the whole test object, with a flow rate high enough to ensure the maximum layer conductivity (later called reference layer conductivity) is reached after 20 to 40 minutes. The test voltage is then applied for maximum 15 minutes if no flashover occurs. Afterwards the insulator is removed from the chamber and allowed to dry. Then, for a second time, the insulator is re-wetted in the chamber until the layer conductivity reaches its maximum value (at least 90% of the reference layer conductivity, otherwise the pollution layer has to be re-applied). The test voltage is then applied again until flashover, or for maximum 15 minutes if no flashover occurs.

For the second procedure, an insulator with a dry pollution layer (expressed through the salt deposit density) is placed into the test chamber. This time the test voltage is applied to the insulator before starting the fog generator. If no flashover occurs the test ends after 100 minutes, or if the measured current peaks fall below 70% of the maximum peak recorded (current peaks decrease due to washing of the pollution layer).

The insulator complies with the specifications, if after a series of three subsequent tests no flashover occurs. If one flashover occurs, the insulator passes the withstand test, if a fourth test is completed successfully without flashover.

2.7 IEC 60060 - High-voltage test techniques [36–38]

Arrangement To avoid proximity effects on the disruptive discharge characteristics all nearby structure should have a clearance of at least 1.5 times the arcing distance.

Atmospheric correction factors The air density or humidity have an impact on the discharge voltage. If the atmospheric conditions during the test vary from the standard referenced atmospheric conditions they have to be corrected according to 2.4 and 2.5. In case of testing the insulator under wetted conditions the humidity correction factor is ignored.

$$K_t = k_1 \cdot k_2 \tag{2.4}$$

K_t Atmospheric correction factor
k_1 air density correction factor
k_2 humidity correction factor

$$U_0 = U/K_t \tag{2.5}$$

U Disruptive-discharge voltage
U_0 corrected voltage

2.7.1 Withstand voltage test

The test voltage is applied to test subject sufficiently slow enough no to cause overvoltages due to switching transients. At 75% of the test voltage the rate of rise is about 2% of the test voltage per second. When the test voltage is reached the voltage is maintained there for 60 seconds. The insulator passes the withstand test if no disruptive discharge occurs on the test subject.

2.7.2 Standard lightning-impulse voltage test

The standard lightning-impulse voltage has, as described in figure 14, a time to peak T_1 of 1.2 μs ± 30% and a time to half-value T_2 of 50 μs ± 20%, shortly described as 1.2/50 impulse. Relevant values are the test voltage, the time parameters and the measured waveform.

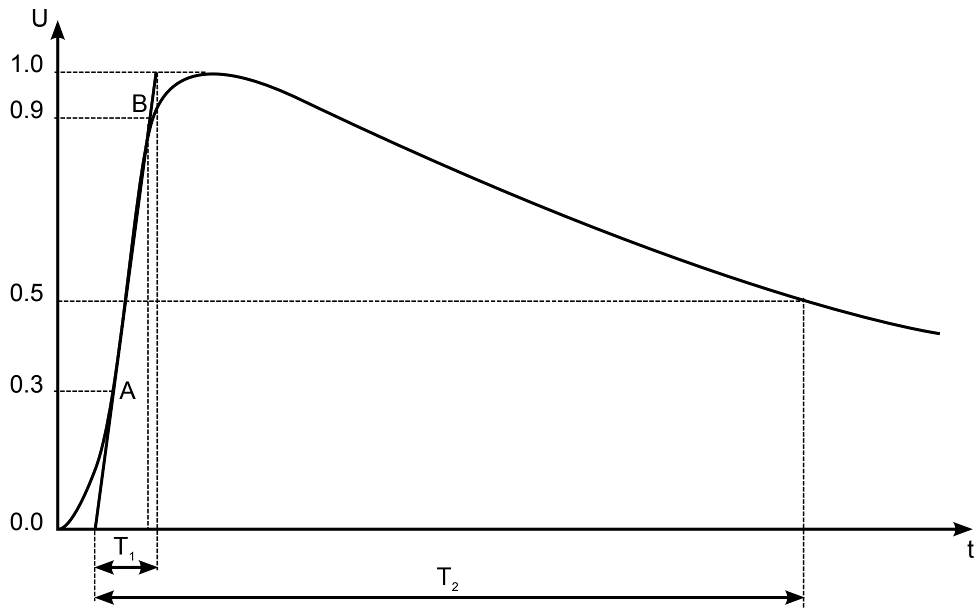


Fig. 14: Full impulse voltage time parameters [39]

To determine the withstand voltage, 4 procedures are described:

A Three impulses at withstand voltage level are applied, no discharge or failure at the non-self-restoring part of the insulation is allowed

B Fifteen impulses at withstand voltage level are applied, a maximum of two discharges and no failure at the non-self-restoring part of the insulation are allowed.

C Three impulses at withstand voltage level are applied, if maximum one discharge occurs at the self-restoring part of the insulation, nine additional impulses are applied. No further discharges are allowed.

D The multiple-level test (figure 38) or the up-and-down withstand method (figure 39) are used to determine the U_{10} and U_{50} voltages. Voltage steps for both methods should be between 1.5% and 3% of the estimated value of U_{50}. The multiple-level test with at least 4 voltage levels and 10 impulses per level, or the up-and-down withstand method with 1 impulse per group and at least 20 applications, are used to determine the value of U_{50}. The up-and-down withstand method with 7 impulses per group and at least eight groups is used to determine the U_{10} value. Start value of the up-and-down methods is the approximated U_{50} value. If the applied impulse causes a disruptive discharge the voltage is decreased, otherwise it is increased. The value of U_{50} is determined by 2.6.

$$U_{50} = \frac{\sum n_v \cdot U_v}{\sum n_v} \tag{2.6}$$

n_v number of impulses

U_v voltage level

$$U_{10} = U_{50}(1 - 1.3s) \tag{2.7}$$

The value of the standard deviation can be set to s = 0.03 for dry test on air insulation.

2.7.3 Standard switching-impulse voltage test

The standard switching-impulse voltage has, as described in figure 14, a time to peak T_1 of 250 $\mu s \pm 20\%$ and a time to half-value T_2 of 2500 $\mu s \pm 60\%$, expressed in short as 250/2500 impulse.

The same test procedures apply as for the lightning-impulse voltage. The value of the standard deviation can be set to s = 0.06 for dry and wet tests on air. insulation.

2.8 IEC 60071 - Insulation co-ordination

IEC 60071 specifies the procedures for the selection of withstand voltage and gives a list of the standard withstand voltages from which the rated withstand voltages should be selected. Table 9 shows relevant insulation levels for the purpose of this thesis [34, 35].

2.9 IEC 60672 - Ceramic and glass insulating materials

IEC 60672 is a three-part international standard for ceramic and glass-insulating materials. Part 1 gives definitions and classifications for nine groups of ceramic material compositions. This work focusses on the group C100, the group of alkaline aluminosilicates, especially in the material composition C130, which was the material of choice for the tested station post insulators. C130 is a non-refractory ceramic with an impressive strength for high-tension insulators. Part 2 specifies test methods to provide test results typical of the material. Part 3 shows the specifications for the individual materials. The material characteristics of the insulators tested in this investigation are shown in table 1 [7, 9, 10].

Standard rated lightning impulse withstand voltage	Highest voltage for equipment Um	Standard rated switching impulse withstand voltage		
		Longitudinal insulation	Phase-to-earth	Phase-to-phase
kV (peak value)	kV (r.m.s. value)	kV (peak value)	kV (peak value)	(ratio to the phase-to-earth peak value)
1300	420	950	950	1.5
1300	420	950	1050	1.5
1300	550	950	950	1.7
1300	550	950	1050	1.6
1425	420	950	1050	1.5
1425	550	950	1050	1.6
1425	550	950	1175	1.5
2100	800	1300	1550	1.6
2100	1100	1425	1550	1.7
2550	1100	1675	1800	1.6
2550	1200	1800	1950	1.6

Tab. 9: Standard insulation levels for range II ($U_m > 245\ kV$) [35]

2.10 ANSI C29.9-1983 (R2002) - Wet Process Porcelain Insulators (Apparatus, Post Type) [40]

This American National Standard defines the dimensions and characteristics of porcelain outdoor high-voltage post-type insulators and specifies the type and regulations of tests to proof the characteristics of a test object.

The following inspection tests have to be performed on every insulator during the manufacturing process:

- Tension test with 50% of rated load
- Cantilever test with 40% of rated load
- Bending moment test with 40% of rated load

The following sample tests have to be performed on a random selection of insulators during the manufacturing process:

- Visual and Dimensional Tests
- Porosity Test
- Galvanizing Test
- Cantilever Strength
- Tensile Strength

The following design tests have to be performed on a selection of insulators after introducing a new design:

- *Low-Frequency Wet Withstand*: Three randomly selected insulators have to be tested. No failure to meet the rated wet withstand value is allowed.
- *Critical-Impulse Flashover - Positive*: Three randomly selected insulators have to be tested. The design fails if the average critical-impulse flashover value is $\leq$ 92% of the rated critical-impulse flashover value.
- *Impulse Withstand*: Three randomly selected insulators have to be tested. No failure to meet the rated impulse-withstand value is allowed.
- *Radio-Influence Voltage (RIV)*: Three randomly selected insulators have to be tested. If one failure occurs, again three random selected insulators have to be tested. Now no failure to meet the rated wet withstand value is allowed.
- *Thermal Shock*: Three randomly selected insulators have to be tested for ten test cycles to switch between a 66°C and 4°C water bath. If one failure occurs, again three randomly selected insulators have to be tested. In total, one failure to meet the electrical soundness is allowed.
- *Compression and Torsional Strength*: Three randomly selected insulators have to be tested. The design fails if the average strength is less than the required strength and if a single test value is $\leq$ 85% of the rated strength.
- *(Optional) Low-Frequency Dry Flashover*: Three randomly selected insulators have to be tested. The design fails if the average dry-flashover value is $\leq$ 95% of the rated dry-flashover value.
- *(Optional) Low-Frequency Wet Flashover*: Three randomly selected insulators have to be tested. The design fails if the average wet-flashover value is $\leq$ 90% of the rated wet-flashover value.
- *(Optional) Critical Impulse Flashover - Negative*: Three randomly selected insulators have to be tested. The design fails if the average critical-impulse flashover value is $\leq$ 92% of the rated critical-impulse flashover value.

Table 10 shows the relevant dimensions and characteristics for an insulator with a basic impulse insulation level of BIL 1300. We can see two obvious differences to the IEC standard. First, at 2692 mm, the overall height of the insulator is lower than the 2900 mm in the IEC standard. Second, the creepage distance is given as 5867 mm, which lies between the IEC nominal creepage distances of 5100 mm and 7000 mm. A comparison with the previous issues from the years 1961 and 1988 has shown, that the relevant dimensions and characteristics haven't changed [41, 42].

BIL Rating	Overall Height	Low-Frequency Test Voltge	Max RIV at $1MHz$	Creepage Distance	Critical Impulse Flashover, Positive	Low-Frequency Wet Withstand	Impulse Withstand
kV	mm	kV	μV	mm	kV	kV	kV
1300	2692 ± 4	220	1000	5867	1410	525	1300

Tab. 10: ANSI defined specifications for a Basic Impulse Insulation Level of BIL 1300 [40]

2.11 ANSI C29.1-1988 (R2002) - Test Methods for Electrical Power Insulators [43]

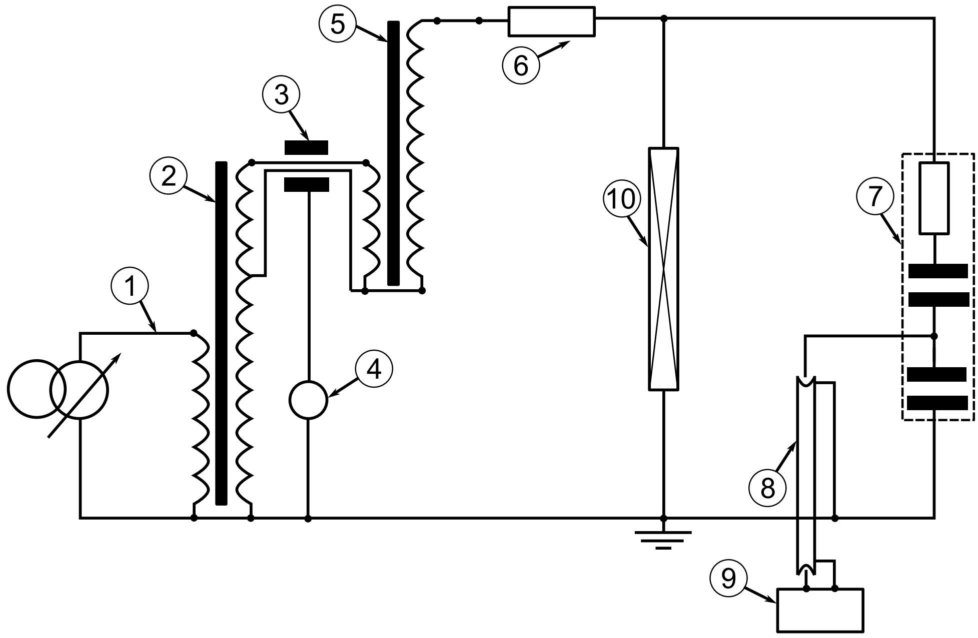
Low-Frequency Wet Flashover Voltage Tests The 75% value of the expected wet flashover voltage value, i.e. the r.m.s. value of the low-frequency voltage causing a lasting flashover through the surrounding medium, is applied to the test subject and then raised gradually. The flashover should occur after 5 to 30 seconds. The test is repeated a minimum of five times after a period of 15 seconds to 5 minutes. The wet flashover voltage value is obtained by calculating the mean value of the measurement results, corrected for air density if the ambient conditions vary from the standard conditions.

Low-Frequency Wet Withstand Voltage Tests The 75% value of the rated withstand voltage, i.e. the r.m.s. value of the low-frequency voltage not causing a flashover or puncture, is applied to the test subject and raised. The rated value should be reached within 5 - 30 seconds, then it is held for 10 seconds. Corrections for the test voltage are according to equation 2.8 and figure 15 shows an example for a test circuit measuring the withstand voltage.

$$V = V_s \cdot \delta \tag{2.8}$$

V: test voltage in kV
V_s: rated withstand voltage in kV
δ: relative air density

Impulse Flashover Tests A 1.2/50 μs impulse wave, with a rated peak value of the impulse causing a flashover through the surrounding medium, is applied to the test subject under dry conditions. The critical impulse flashover voltage value, i.e. the peak value of the impulse which has a 50% probability of causing a flashover through the surrounding medium, is determined with regard to a correction to standard conditions.



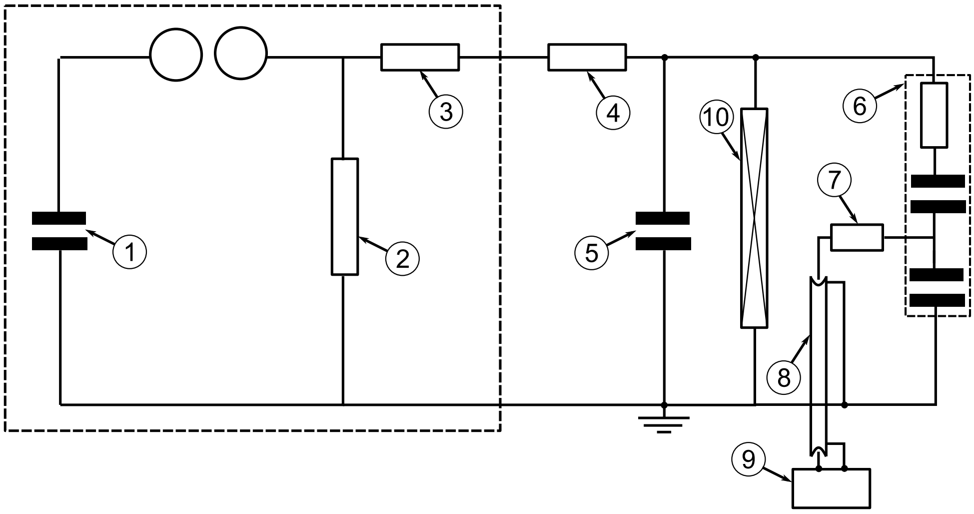
1	Variovolt
2	Transformer
3	Capacitive plug
4	Peak/$\sqrt{2}$ voltmeter
5	Transformer
6	Protective resistance
7	Damped capacitive divider
8	Coaxial cable 75 Ω
9	Peak/$\sqrt{2}$ voltmeter
10	Test sample

Fig. 15: Example for a test circuit for power frequency tests [44]

Impulse Withstand Voltage Test The insulator is exposed to three atmospheric corrected impulse voltages with a peak value higher or equal to the rated impulse withstand value, i.e. the peak value of the impulse not causing a flashover through the surrounding medium. An example for a test circuit measuring the withstand voltage is shown in figure 16.

2.12 ANSI/IEEE Std 4-1978 - IEEE Standard Techniques for High-Voltage Testing [39]

This standard is based on IEC Publications 60060-1, 60060-2, 60060-3, 60060-4 and 60050 and describes lightning impulse voltage and switching impulse voltage test methods that are relevant to this thesis. As in our case the guidelines and tests are the same, this standard does not need to be discussed any further.



1	Impulse generator
2	Internal tail resistance
3	Internal front resistance
4	External front resistance
5	Changing capacitor, capacitive divider
6	Damped capacitive divider
7	Resistance 75 Ω
8	Coaxial cable 75 Ω
9	Measuring equipment: Oscillograph - Peak Voltmeter
10	Test sample

Fig. 16: Example for a test circuit for lightning impulse tests [44]

3 Simulation software

Electric field simulations have been performed using the software ElecNet from Infolytica. ElecNet is a software based on finite element analysis methods to solve 2D/3D static electric field problems [45]. ElecNet allows to simulate the problem in a rotationally symmetric or plane parallel way. Due to the cylindrical form of the insulator the rotationally symmetric arrangement was selected.

Using scripting commands, the software is fully remotely accessible through any OLE automation compatible application (e.g. Microsoft Word®, Microsoft Excel®, Matlab). In our case Microsoft Excel® was used to perform the scripting operations, it was also used to calculate characterizing the insulator profile and and to check the supplied data for plausibility.

3.1 Model solver

To calculate the electric field, ElecNet uses numerical analysis methods to solve the differential equations. In the first calculation step, the area of interest is subdivided into arbitrary elements, the so-called finite elements, and a basic function is applied to it. The Newton-Raphoson-method was used by ElecNet to solve these non-linear equations of our model. For a continuously differentiable equation with one variable it is possible to get approximated values of the solution. The basic idea of this method is to linearise the function from a starting point, meaning calculating the tangent and using the root of the tangent as an improved approximation of the root of the function. The resulting approximation is then a starting point for the next improvement step. The iteration steps when the difference between two successive approximation values falls below a certain predefined limit. [46, 47].

Required settings to solve the basic function in ElecNet are the number of iteration steps, the order of the polynom and the tolerance of the approximation. For a better accuracy it is also possible to reduce the CG-tolerance. The conjugate-gradients-method is an effective numerical method to solve large symmetric positive equations. The h-type-adaption-method can also be used to improve the mesh size. The error of the electric field is compared the specified tolerance. If the limit of tolerance is reached the finite element is bisected and the mesh size is reduced [46].

3.2 Boundary conditions

Numerical analysis methods, such as the finite element method, do not allow an infinite border. The model has to be placed in a finite box. Boundary conditions for the model are necessary to get a unique solution for the differential equations. For the simulation two conditions had to be considered. The so-called Dirichlet condition and the Neumann condition. The Dirichlet condition is used, where the field lines of the E-field respectively D-field are parallel to the border. As the border is not allowed to have an impact on the model, it has to be far off the model. The Dirichlet condition is then applied to the so-called *far border*. In our case an air box, five times the size of the insulator arrangement, was set around the model. The Neumann condition, the other boundary condition, is set where the field lines of the E-field are normal to the border. No parallel components are allowed, meaning there is no change of the potential. The Neumann condition is usually used for the earth potential, as well as for electrodes with a potential uneven to zero [46].

3.3 Material properties

The used material properties for the model are shown in table 11.

material	**zement filling**	**ceramic**	**aluminium fitting**
permittivity ε	9	8	1
specific resistance Ω/cm	$1 \cdot 10^{-6}$	$1 \cdot 10^{-13}$	$3.8 \cdot 10^{7}$

Tab. 11: User material properties for the simulation

3.4 Scripting macro

Figure 17 shows the main user interface of the Microsoft Excel® macro. Block 1 on the left side marks the buttons to activate the ElecNet scripting commands. The buttons should mainly be pressed in the order they are arranged. Naturally, the button *"Start ElecNet"* is used to start the application. Per default, the software starts as a background application, so the button *"ElecNet Visibility"* has to be pressed in order to make it visible. If all supplied data (blocks 2, 3 & 5) passes the plausibility check (block 10) and all insulator parameters are green, the button *"Draw Model"* is used to draw the model in ElecNet, including setting the material properties,

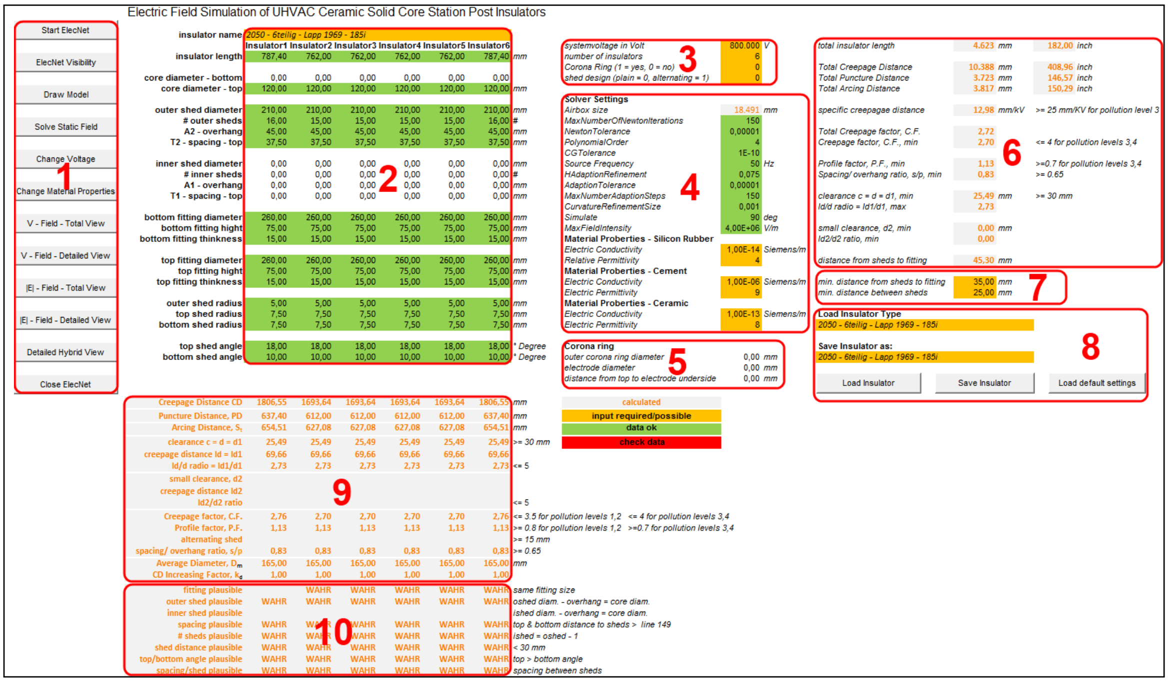


Fig. 17: Microsoft Excel® Macro for ElecNET Electric Field simulation

system voltage and boundary conditions. The button *"Solve Static Field"* activates the problem solver and calculates the field intensity and voltage characteristic of the given model. In its first run the solver delivers a rough approach of the solution. Only after activating the button for a second time the solver calculates the field problem with the given settings. *"Change Voltage"* and *"Change Material Properties"* can be used to apply different settings to the given model and run the solver again. The *"View"* Buttons are used to compare different insulator arrangements. *"V-Field - Total View"* shows the Voltage Characteristic of the total insulator arrangement, *"V-Field - Detailed View"* shows approximately one meter of the insulator arrangement holding the system voltage. *"E-Field - Total View"* and *"E-Field Detailed View"* show the same sections but this time instead of the voltage characteristic the field intensity is displayed, standardized to a maximum value of $4 \cdot 10^6 kV/mm$. Activating *"Detailed Hybrid View"* is showing the top section of the insulator arrangement with a shaded plot of the field intensity and a contour plot of the voltage characteristic.

The main input section (block 2) is for describing the insulator profile. Up to a stack of 6 insulator units can be described for modelling. Before entering data in block 2, the number of insulators and the shed design should be checked in block 3. Setting this parameter will enable the required fields in block 2. The required inputs can be divided into 3 groups: 1) The basic shed settings, describing the diameter of the sheds, the number of sheds, the spacing and overhang. 2) The fitting foam, describing the height of the fitting and diameter and thickness of the mounting plate. 3) The detailed shed settings, describing the shed angles and radii. In block 4, the parameters for the solver setting and material properties are defined. The standard solver setting deliver the highest possible resolution for solving the problem, but they are also the most time consuming. If alternative material properties are intended to be tested, they can also be entered here. If the corona ring option is enabled in block 3, profile parameters have to be entered in block 5.

Block 9 contains the parameters characterizing each insulator profile. The creepage distance CD is the shortest distance along the insulator surface connecting the fittings. The puncture distance PD is the shortest distance through the insulator material connecting the fittings. The arcing distance S_t is the shortest distance outside the insulator connecting the fittings. The clearance c is the shortest distance from the lowest point of the shed to the shed beneath. The creepage distance ld is the distance between the two points along the insulator surface which define c. The small clearance is the clearance from the alternating shed with the smaller diameter to the shed beneath. The creepage factor $C.F.$ is the ratio of the creepage distance to the arcing distance and is defined by equation 1.22. The profile factor is defined by equation 1.23. Recommendations of the IEC for the calculated values are given in table 2. A visual summary of the profile parameters is shown in figure 8. Parameters characterizing the entire insulator are shown in block 6. The total creepage distance, puncture distance and arcing distance are given, as well as the specific creepage distance. The total creepage factor, defined by equation 1.22 is also calculated, as well as the worst creepage factor of a single section. The minimum clearance for the plain and alternating sheds is calculated, as well as their corresponding creepage distance. Finally, the distance between the outermost point of the fitting and the outermost point of the shed is calculated.

The results of the plausibility check are shown in block 10. If the given data in block 2 fails a check, the concerning fields are marked red, if they pass the test, the fields are green. *"Fitting plausible"* checks if the fittings of two consecutive insulators have the same diameter. *"Outer shed plausible"* checks if the product of the core diameter and overhang A2 is the outer shed diameter. If an alternating shed design is selected *"Inner shed plausible"* checks if the product of the core diameter and overhang of A1 is the inner shed diameter. *"Shed distance plausible"* checks if the distance between the outermost point of the fitting and the outermost point of the shed is greater as the input value given in block 7. *"Shed distance plausible"* checks if the smallest clearance is smaller than the input value given in block 7. *"Top/bottom angle plausible"* checks if the top angle is greater than the bottom angle. *"Spacing/shed plausible"* checks if the drawn shed, given by its input values would be within the available spacing.

4 Results of the Type Tests

Type tests are performed to verify new profile characteristics of a test subject for a given insulation level. Seven type tests were compared in accordance with IEC and ANSI standards for test objects with a similar switching impulse withstand voltage in wet conditions. Four groups of insulators with a dry lightning impulse withstand voltage of 1300 kV, 1425 kV, 2050 kV and 2550 kV have been investigated. The insulators of each group had similar mechanical characteristics with the great difference in number of insulator units and accordingly different single unit length. The oldest insulators investigated consisted of more and shorter units, the latest insulators had an improved shed profile, and less and longer single units. The profile characteristics of all insulators in this investigation have been tested through electric field simulations in a later part of this work.

4.1 IEC standard tests

Test objects according to IEC standard:

1 C12.5-2550 - 3 units - length = 5700 mm [48]

2 C20-1425mod - 1 unit - length = 2850 mm [49]

3 C20-1425 - 2 units - length = 3150 mm [50]

For insulators with a dry lightning impulse withstand voltage of 2550 kV there was only one type test report available, but the results are shown anyway to get a sense for the results. For insulators with a dry lightning impulse withstand voltage of 1425 kV there were reports for 2 test objects available. One test object had a standard insulator profile without a corona ring, the other test object had a 300 mm shorter insulator profile, tested once with and without corona ring. Table 12 shows the comparison of the lightning impulse voltage test in dry conditions, table 13 shows the comparison of the switching impulse voltage test in dry an wet conditions, table 14 shows the comparison of the power frequency withstand voltage test in dry and wet conditions according to the IEC standards. All insulator profiles passed the type tests, even the shorter non-standard version. However, due to the lack of data and type tests, it is not possible to give general recommendations for an alternative insulator profile at this point.

Insulator Type	Length mm	Number of units	Corona Ring	Spec. min. LIV kV_{peak}	U50% LIV tested +/- kV_{peak}	U10% LIV tested +/- kV_{peak}	Impulses/ Flashover +/-
C12.5-2550	5700	3	yes	2550	+3364/ -3384	+3235 -	15/2 15/0
C20-1425mod	2850	1	yes	1425	+1630/ -1748	+1567/ -1680	15/0 15/0
C20-1425mod	2850	1	no	1425	+1700/ -1798	+1635/ -1730	15/0 15/0
C20-1425	3150	2	no	1425	+1782/ -1874	+1712/ -1801	15/0 15/0

Tab. 12: IEC Lightning impulse voltage test in dry conditions

Insulator Type	Length mm	Number of units	Corona Ring	Spec. min. SIV kV_{peak}	U50% SIV tested (dry / wet) kV_{peak}	U10% SIV tested (dry / wet) kV_{peak}	Impulse/ flashover (dry / wet)
C12.5-2550	5700	3	yes	1550	+1989/ -2634 +1935/ -2404	+1833/ - +1783/ -	15/0 15/0
C20-1425mod	2850	1	yes	950	- +1175/ -1429	- +1082/ -1316	- 15/2
C20-1425mod	2850	1	no	950	- +1247/ -1331	- +1149/ -1226	- 15/2
C20-1425	3150	2	no	950	+1386/ -1696 +1231/ -1435	+1278/ -1564 +1135/ -1323	15/0 15/0

Tab. 13: IEC Switching impulse voltage test in dry and in wet conditions

Insulator Type	Length mm	Number of units	Corona Ring	Spec. min. FWV $kV_{r.m.s.}$	Rain mm/min	Power frequency withstand voltage (dry / wet) $kV_{r.m.s.}$	Flashover/ Puncture
C12.5-2550	5700	3	yes	870	v:2 h:1.9	1268/1254	no
C20-1425mod	2850	1	yes	575	v:1.1 h:1.8	-/638	no
C20-1425mod	2850	1	no	575	v:1.1 h:1.8	-/618	no
C20-1425	3150	2	no	575	v:1.5 h:1.5	-/707	no

Tab. 14: IEC power frequency withstand voltages test in dry and wet conditions

4.2 ANSI standard tests

ANSI standard tests were performed on four insulators. Two insulators had a basic impulse insulation level of BIL 1300, two had BIL 2050. The definition of the basic impulse insulation level is similar to the IEC definition of the dry lightning impulse withstand voltage. Both pairs of test subjects had the same total height, only the number of single insulation units varied. ANSI standard insulators with BIL 1300 have a height of 2692 mm, meaning they are 208 mm shorter than the equivalent insulator characterised regarding the IEC standard. Table 15 shows the comparison of the impulse withstand and flashover voltage tests, table 16 shows the comparison of the low-frequency wet withstand and flashover voltage tests according to the ANSI standards. The following test objects have been tested according to ANSI standard:

1 TR368 - 1 unit - length = 2692 mm [44]

2 TR369 - 2 units - length = 2692 mm [51]

3 C20-2050 HT - 2 units - length = 4699 mm [52]

4 C20-2050 HT - 3 units - length = 4699 mm [53]

Insulator Type	Length mm	Number of units	Corona Ring	Guaranteed applied voltage kV	Guaranteed flashover voltage kV	Spec. min. impulse flashover voltage kV_{peak}	V_{CRA} kV_{peak}	Impulses/ Flashover
TR. 368	2692	1	no	1300	1410	1297	1528	3/0 3/0 3/0
TR. 369	2692	2	no	1300	1410	1297	1489 -1651	3/0 3/0 3/0 3/0 3/0 3/0
2050 HT	4699	2	Yes	2050	2250	2070	2657	3/0 3/0 3/0
2050 HT	4699	3	Yes	2050	2250	2070	2684	3/0 3/0 3/0

Tab. 15: ANSI Impulse Withstand and Flashover Voltage Tests

Insulator Type	Lenght mm	Number of units	Corona Ring	Rated Critical Voltage kV	Rain mm/min	V_{FS} kV	V_{FA} kV	Flashover
TR. 368	2692	1	no	525	5	525/525/525	525	no/no/no
TR. 369	2692	2	no	525	5	550/540/540	543	no/no/no
2050 HT	4699	2	yes	830	5.3	830/830/830	830	no/no/no
2050 HT	4699	3	yes	830	4.6	830/830/830	830	no/no/no

Tab. 16: ANSI Low-Frequency Wet Withstand and Flashover Voltage Tests

5 Results of the Field Simulation

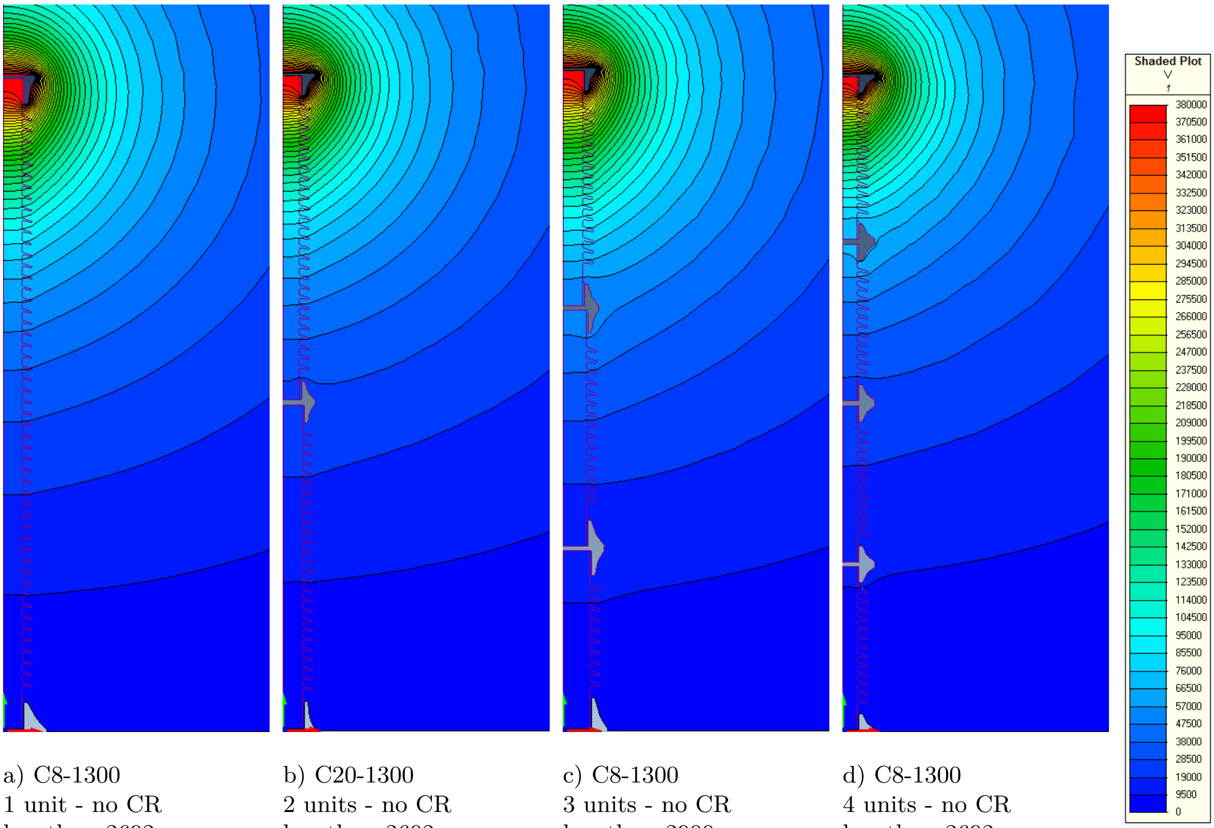
In total, 24 electric field simulations have been performed using ElecNet and the Microsoft Excel® Macro. Four groups of insulators with a dry lightning impulse withstand voltage of 1300 kV, 1425 kV, 2050 kV and 2550 kV have been investigated. The insulators of each group had similar mechanical characteristics with the great difference of single insulator unit length. The oldest insulators investigated consisted of more and shorter units, the latest insulators had an improved shed profile and longer single unit length.

The focus of this investigation was on the voltage characteristic and field intensity of the latest insulator designs. It was important to figure out if station post insulators with a given dry lightning impulse withstand voltage still have to have the same total insulator height, even if the profile and electrical characteristics have improved over the last decades.

Although the simulations have no significance regarding partial discharge, they can be used to detect critical parts of the insulator arrangement where partial discharge could occur. Measures could be taken to reduce the field intensity, like changing the design or selecting other materials. A fact that also needs to be taken into account is that the field simulations act on the assumption that the insulator surface is clean. A pollution layer could mess up some considerations.

5.1 Comparison of the electrostatic field simulations for BIL 1300 insulators

Figure 18 shows the simulated voltage characteristic of the four tested insulator arrangements with a dry lightning impulse withstand voltage of 1300 kV, test voltage was 380 kV. Insulator a) consists of 1 unit with a length of 2692 mm and has the latest advanced shed design (year 2009) with very thin sheds and a creepage distance of about 6000 mm. Insulator b) consists of 2 units with a total length of 2692 mm and has an advanced shed design (year 2002) with a creepage distance of about 5930 mm. Insulator c) consists of 3 units with a total length of 2900 mm and has an older shed design (year 1969) with a nominal creepage distance of 5100 mm. Insulator d) consists of 4 units with a total length of 2692 mm, it was produced by a competing company (year 1970). Figure 19 shows a comparison of the combined field intensity and voltage



a) C8-1300
1 unit - no CR
length = 2692 mm

b) C20-1300
2 units - no CR
length = 2692 mm

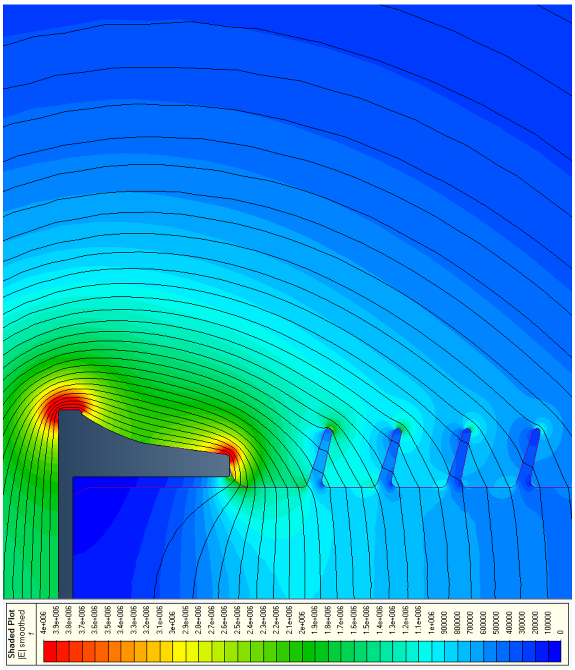
c) C8-1300
3 units - no CR
length = 2900 mm

d) C8-1300
4 units - no CR
length = 2692 mm

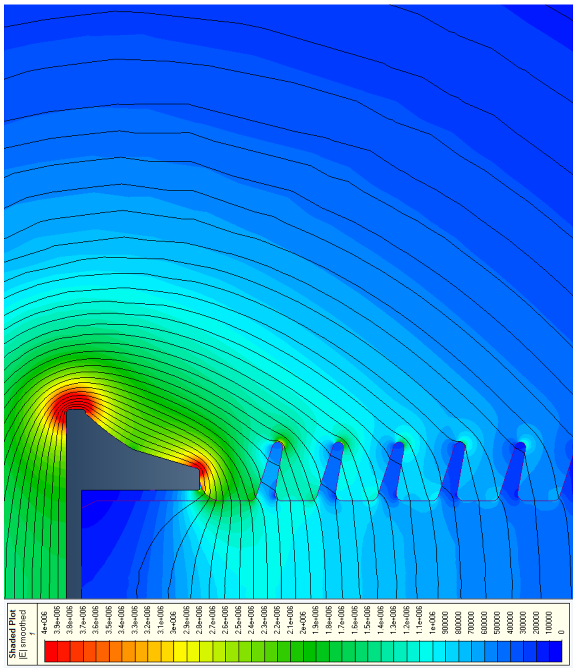
Fig. 18: Comparison of the voltage characteristic for various insulator arrangements for BIL1300 - total insulation arrangement

characteristic plot of the top section of each insulator arrangement. The contour plot represents the voltage characteristic previously shown in figure 18. The shaded plot represents the field intensity standardized to a maximum value of $4 \cdot 10^6 kV/mm$. Obvious hot spots are near rough edges of the top fitting and between the outermost and lowest point of the first sheds.

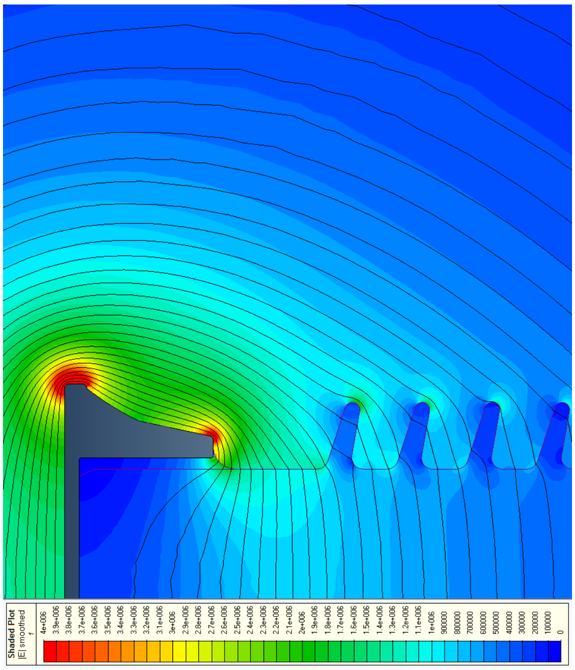
Figure 20 shows the graphs of the comparison of the field intensity for the various insulator arrangements. Graph a) shows the course of the electric field for the whole insulator arrangement along the outermost point of the shed, chart b) shows a more detailed view of the first meter of the energized side of the insulator. As seen in figure 19 the outermost point holds the highest field intensity and is therefore critical for discharge or flashover. The highest field intensity can be measured at the first shed. Along with the voltage, it is rapidly decreasing. It can be seen that the further the distance between the first shed and the top fitting, the less is the field intensity. Figure 21 shows the graphs of the comparison of the voltage characteristic for the various insulator arrangements. Graph a) shows the voltage characteristic for the whole insulator arrangement along the outermost point of the shed, graph b) shows a more detailed view of the voltage characteristic along the first meter of the energized side of the insulator. The graphs show for insulators with the same total height that the more single insulation units an insulator arrangement has the faster the voltage is decreasing. Due to the direct relationship of the voltage with the field intensity this fact could reach critical values for the first sheds and could cause partial discharge or flashover.



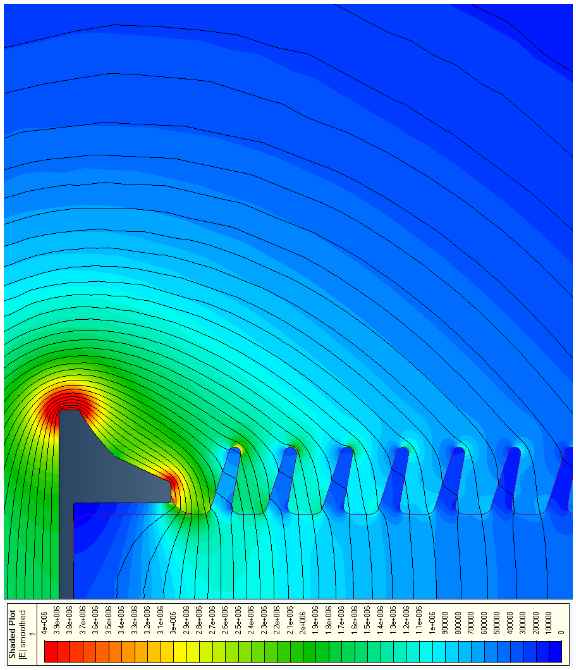
a) BIL C8-1300 - 1 unit - no CR - l = 2692 mm



b) BIL C20-1300 - 2 units - no CR - l = 2692 mm

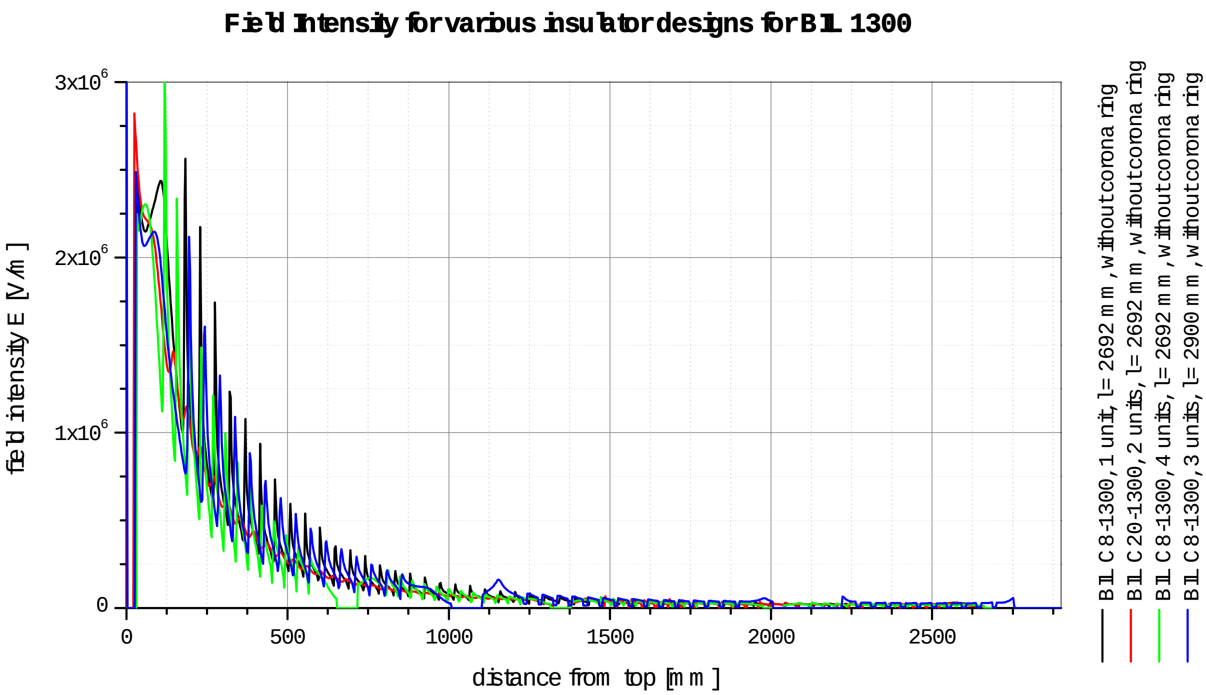


c) BIL C8-1300 - 3 units - no CR - l = 2692 mm

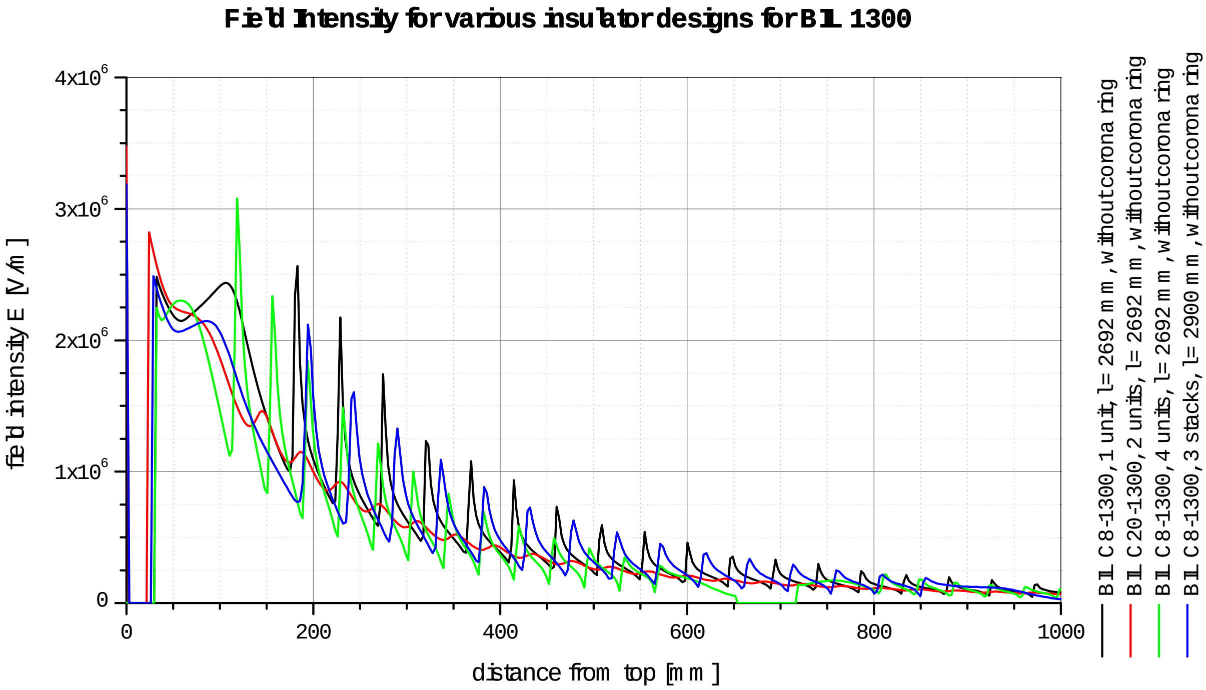


d) BIL C8-1300 - 4 units - no CR - l = 2692 mm

Fig. 19: Comparison of the field intensity and voltage characteristic for various insulator arrangements for BIL1300 - detailed view of the top fitting

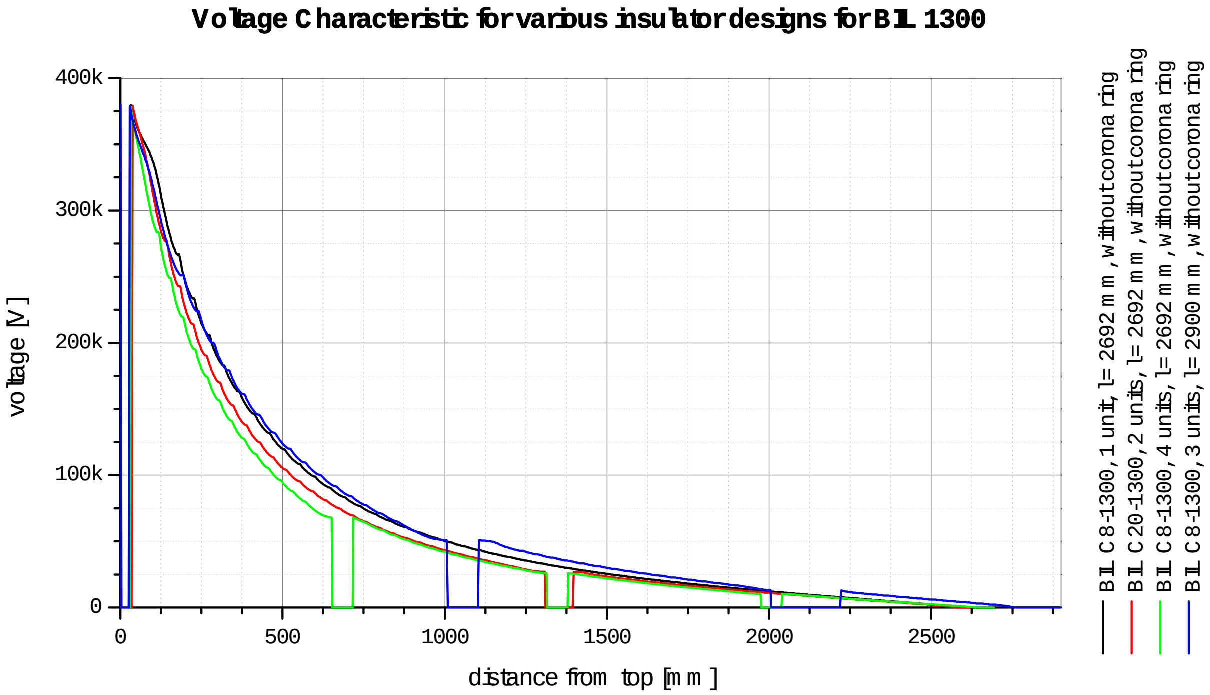


a) Course of the electric field for the whole insulator along the outer shed

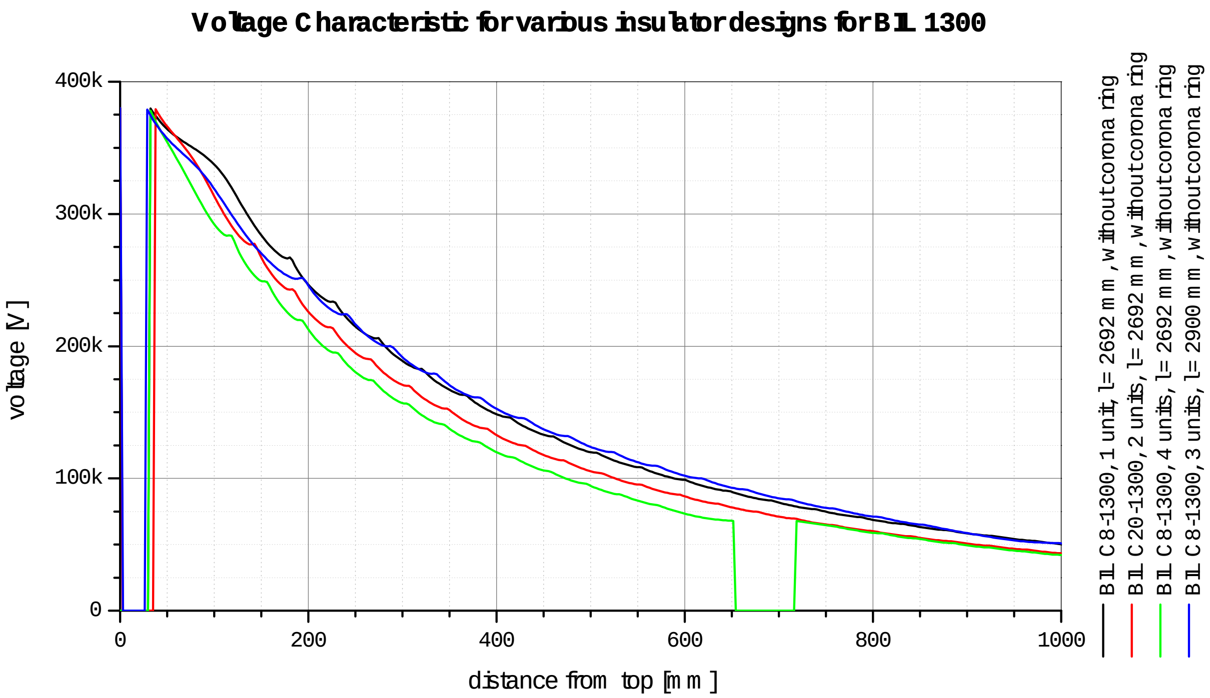


b) Course of the electric field for the first meter from the top along the outer shed

Fig. 20: Comparison of the field intensity for various insulator arrangements at BIL1300



a) Voltage Characteristic for the whole insulator along the outer shed



b) Voltage Characteristic for the first meter from the top along the outer shed

Fig. 21: Comparison of the voltage characteristic for various insulator arrangements at BIL1300

5.2 Comparison of the electrostatic field simulations for BIL 1425 insulators

Figures 22 and 23 show the simulated voltage characteristic of the seven tested insulator arrangements with a dry lightning impulse withstand voltage of 1425 kV, test voltage was 400 kV. The insulators in figure 22 are modified to a length of 2850 mm, the insulators in figure 23 are the once with the standard length of 3150 mm. Insulator 22a) consists of 1 unit and has the latest advanced shed design (year 2009) with very thin alternating sheds and a creepage distance of about 11800 mm. Insulator b) is the same as shown in a) but has no corona ring. Insulator c) also consists of 1 unit but has a weaker bending load and a creepage distance of about 10600 mm. Insulator d) is the same as shown in c) but has no corona ring.

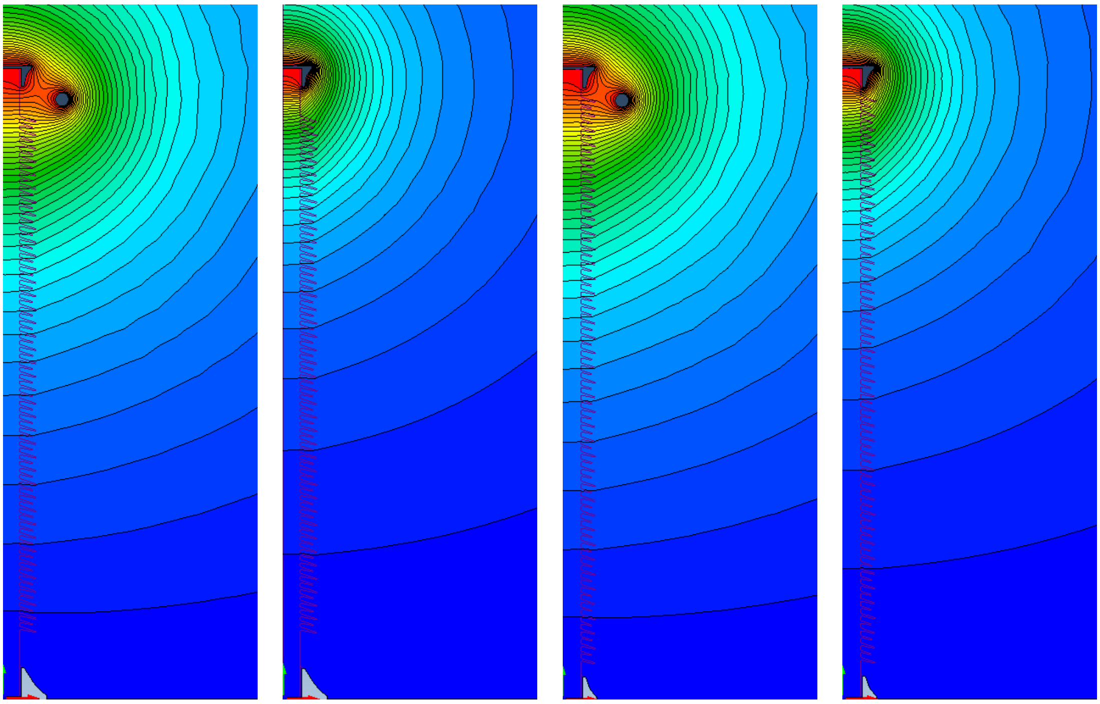
Insulator 23a) consists of 2 units with an advanced alternating shed design (year 2006) and a creepage distance of about 10900 mm. Insulator b) is the same as shown in a) but has no corona ring. Insulator c) consists of 3 units with an older shed design (year 1970) and a creepage distance of about 5600 mm, also no corona ring is attached.

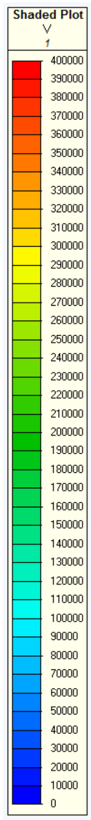
Figures 24 and 25 show a comparison of the combined field intensity and voltage characteristic plot of the top section of each insulator arrangement. The contour plot represents the voltage characteristic previously shown in figure 18. The shaded plot represents the field intensity standardized to a maximum value of $4 \cdot 10^6 kV/mm$. Obvious hot spots are near rough edges of the top fitting and between the outermost and lowest point of the first sheds. The effect of the corona ring is also clearly visible, the voltage characteristic is much more homogeneous over the radial section and the voltage decrease is also slower and linearised.

Figure 26 shows the graphs of the comparison of the field intensity for the various insulator arrangements. Graph a) shows the course of the electric field for the whole insulator along the outermost point of the shed, chart b) shows the first meter of the energized side of the insulator. As seen in figures 24 and 25 this point holds the highest field intensity and is therefore critical for discharge or flashover. The highest field intensity can be measured at the first shed, it can be seen that the more space lies between the shed and the top fitting, the less the field intensity.

Figure 27 shows the graphs of the comparison of the voltage characteristic for the various insulator arrangements. Graph a) shows the voltage characteristic for the whole insulator arrangement along the outermost point of the shed, graph b) shows a more detailed view of the voltage characteristic along the first meter of the energized side of the insulator.

The graphs compare insulators of the same total height and show, that more single insulation units in an insulator arrangement cause a faster voltage decrease. All insulators with a corona ring have about the same voltage characteristic with a much slower decreasing voltage. Due to





a) C20-1425mod
1 unit with CR
length = 2850 mm

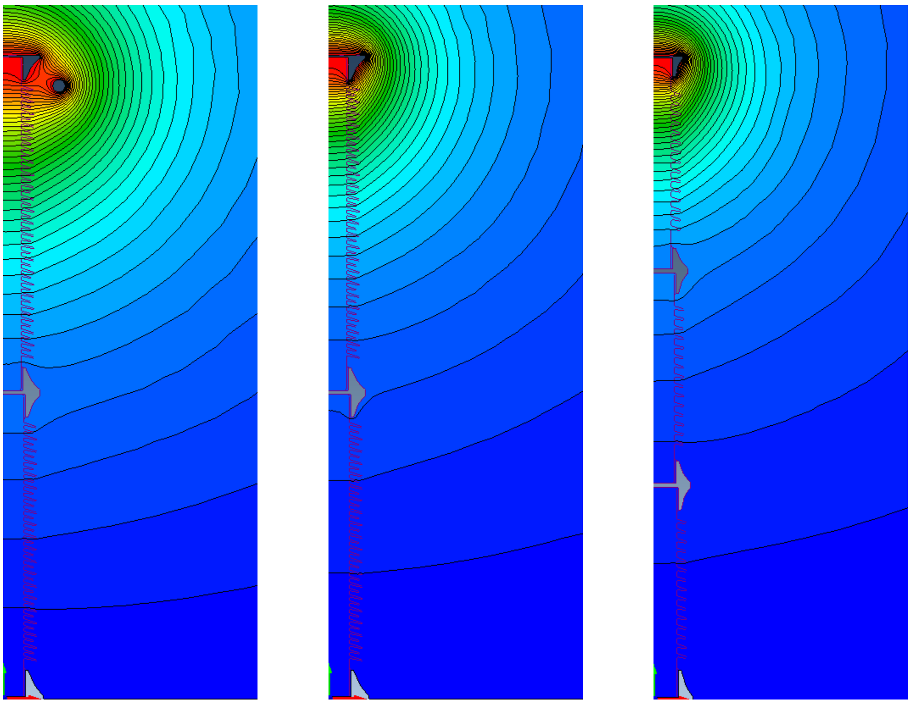
b) C20-1425mod
1 unit - no CR
length = 2850 mm

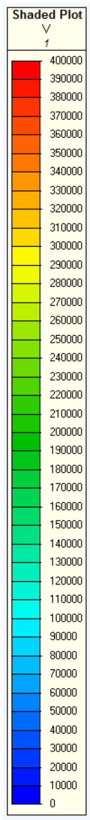
c) C8-1425mod
1 unit with CR
length = 2850 mm

d) C8-1425mod
1 unit - no CR
length = 2850 mm

Fig. 22: Comparison of the voltage characteristic for various insulator arrangements for BIL1425 - part 1 - total insulation arrangement

the direct relationship of the voltage with the field intensity this fact has a positive impact on the field intensity, the highest field intensity on the sheds does not exceed a value of $1 \cdot 10^6 kV/mm$. On the other hand insulators without a corona ring reach the critical flashover value of $3 \cdot 10^6 kV/mm$ for air.



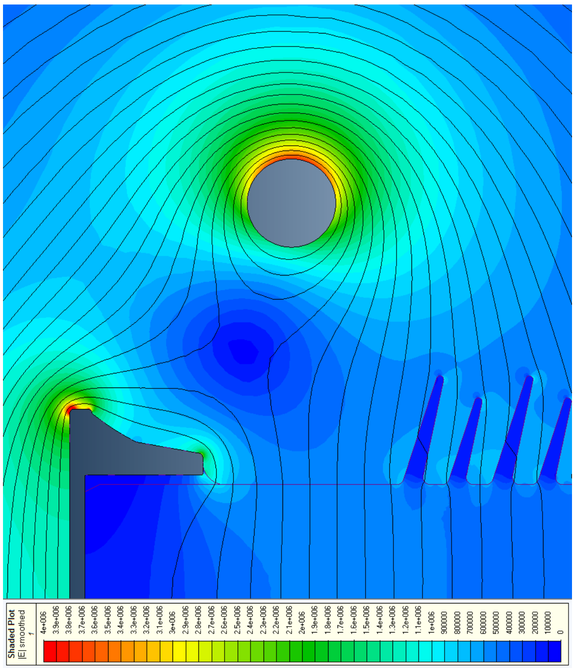


a) C20-1425
2 units with CR
length = 3150 mm

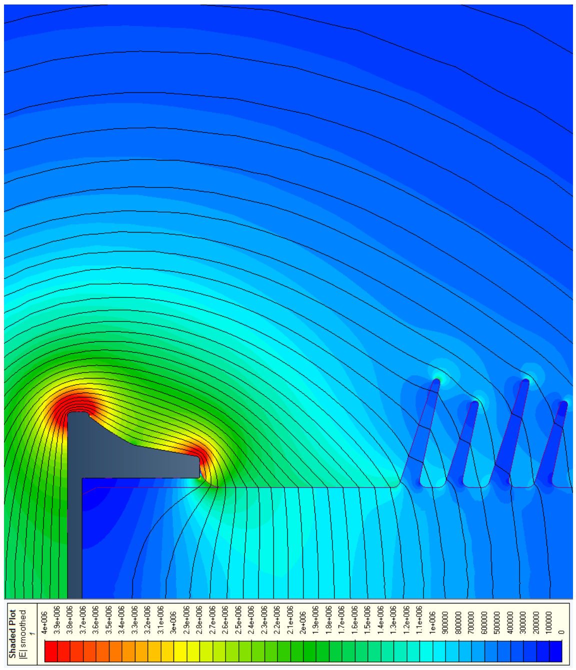
b) C20-1425
2 units - no CR
length = 3150 mm

c) C20-1425
3 units - no CR
length = 3150 mm

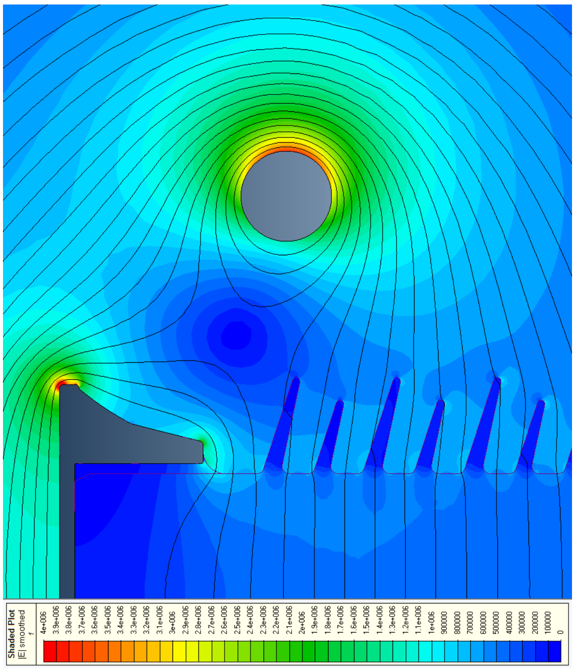
Fig. 23: Comparison of the voltage characteristic for various insulator arrangements for BIL1425 - part 2 - total insulation arrangement



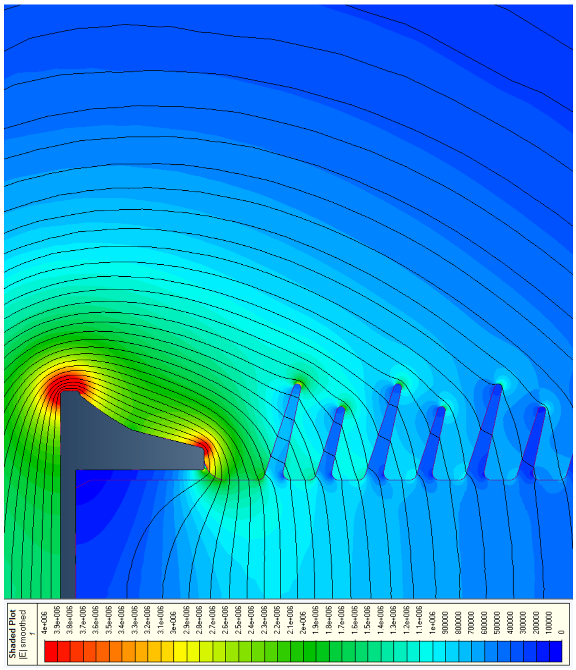
a) BIL C20-1425mod - 1 unit - CR - l = 2850 *mm*



b) BIL C20-1425mod - 1 unit - no CR - l = 2850 *mm*

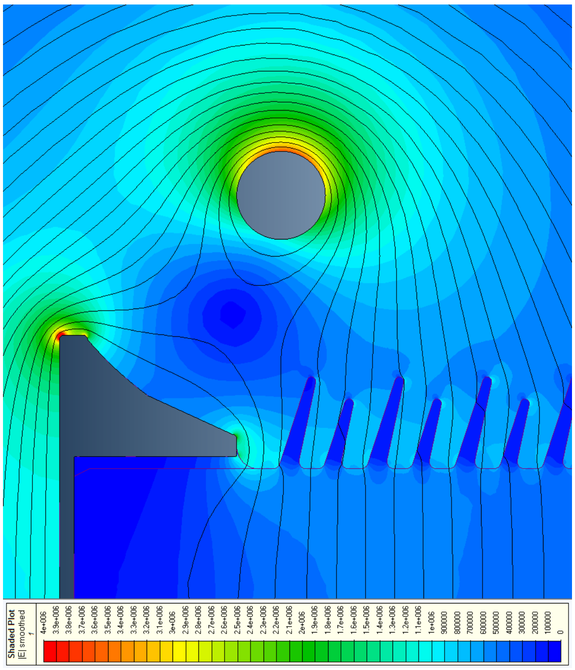


c) BIL C8-1425mod - 1 unit with CR - l = 2850 *mm*

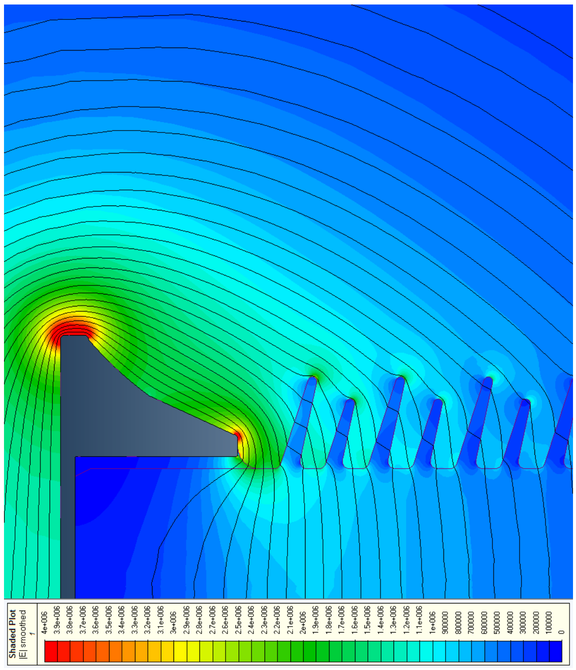


d) BIL C8-1425mod - 1 unit - no CR - l = 2850 *mm*

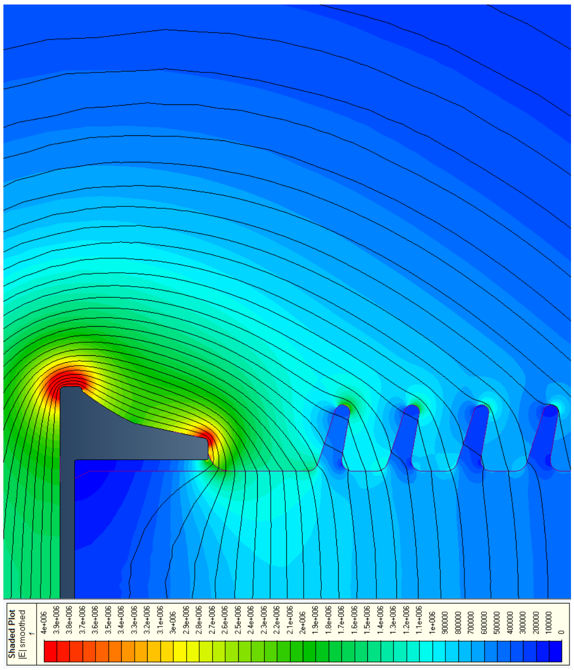
Fig. 24: Comparison of the field intensity and voltage characteristic for various insulator arrangements for BIL1425 - part 1 - detailed view of the top fitting



a) BIL C20-1425 - 2 units with CR - l = 3150 mm

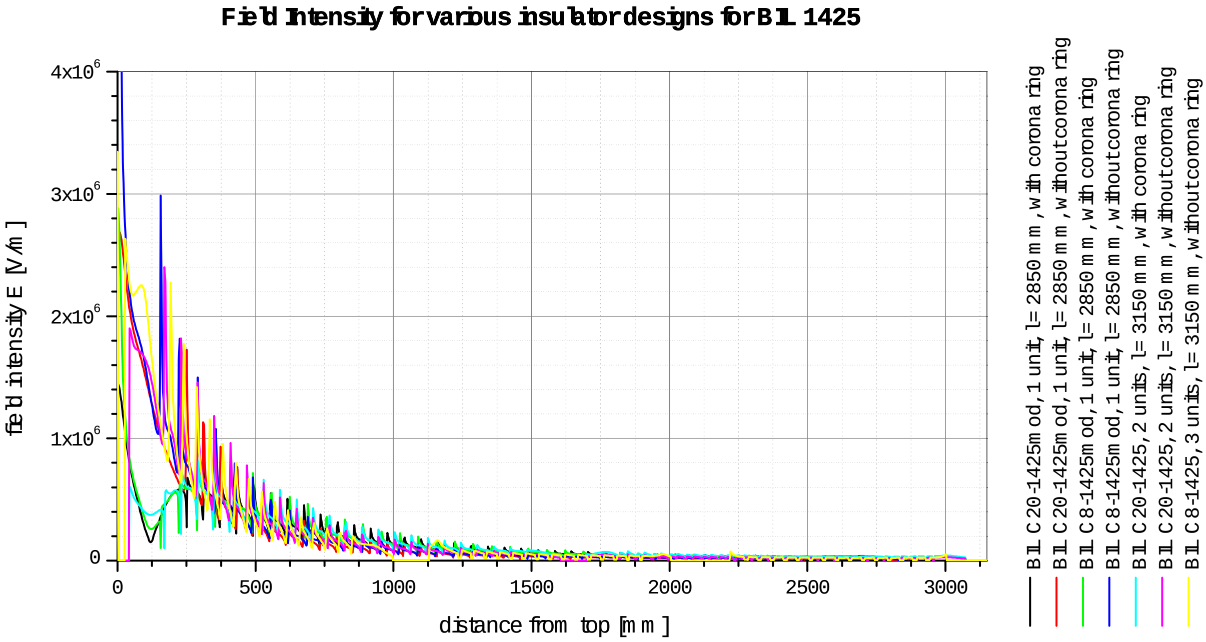


b) BIL C20-1425 - 2 units - no CR - l = 3150 mm

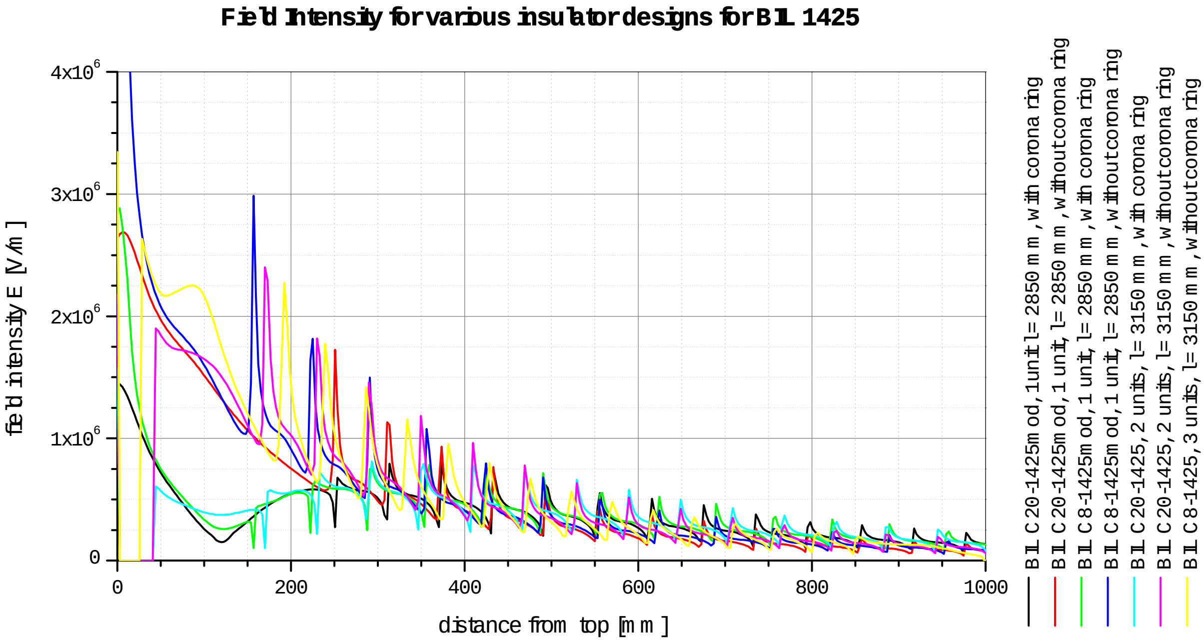


c) BIL C8-1425 - 3 units - no CR - l = 3150 mm

Fig. 25: Comparison of the field intensity and voltage characteristic for various insulator arrangements for BIL1425 - part 2 - detailed view of the top fitting

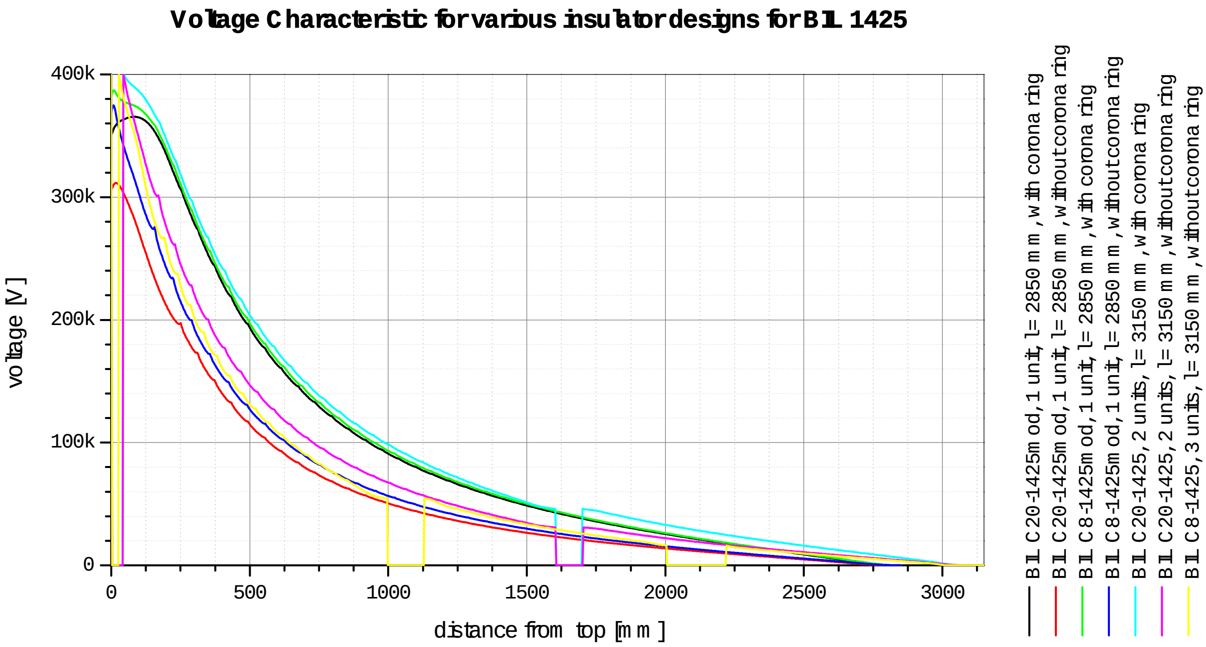


a) Course of the electric field for the whole insulator along the outer shed

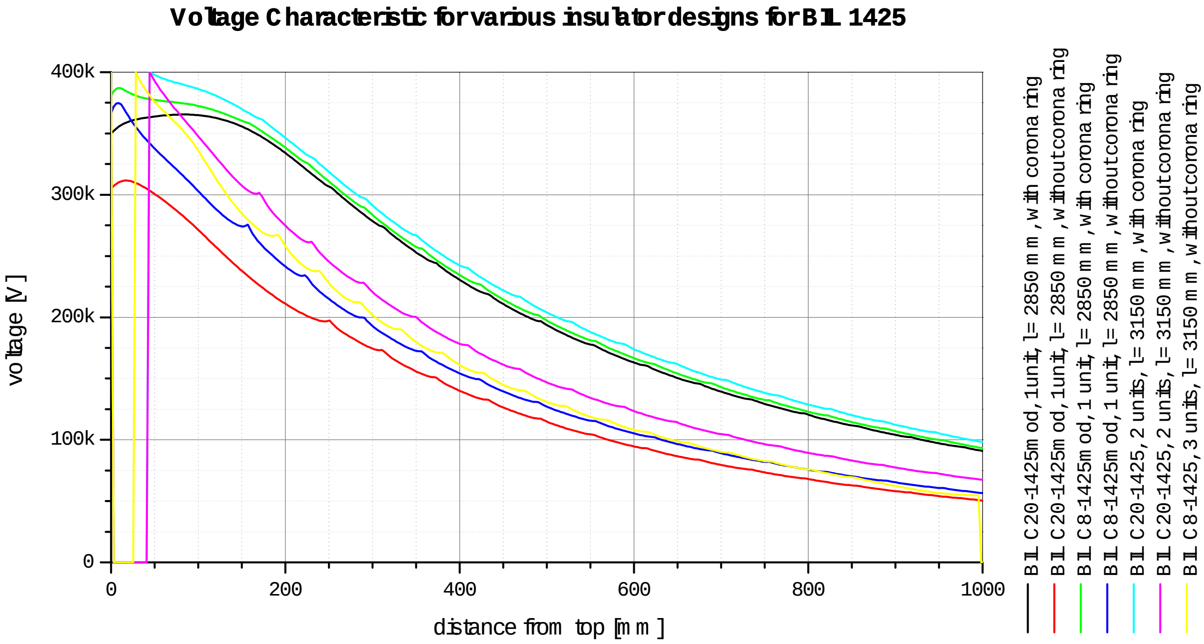


b) Course of the electric field for the first meter from the top along the outer shed

Fig. 26: Comparison of the field intensity for various insulator arrangements at BIL1425



a) Voltage Characteristic for the whole insulator along the outer shed



b) Voltage Characteristic for the first meter from the top along the outer shed

Fig. 27: Comparison of the voltage characteristic for various insulator arrangements at BIL1425

5.3 Comparison of the electrostatic field simulations for BIL 2050 insulators

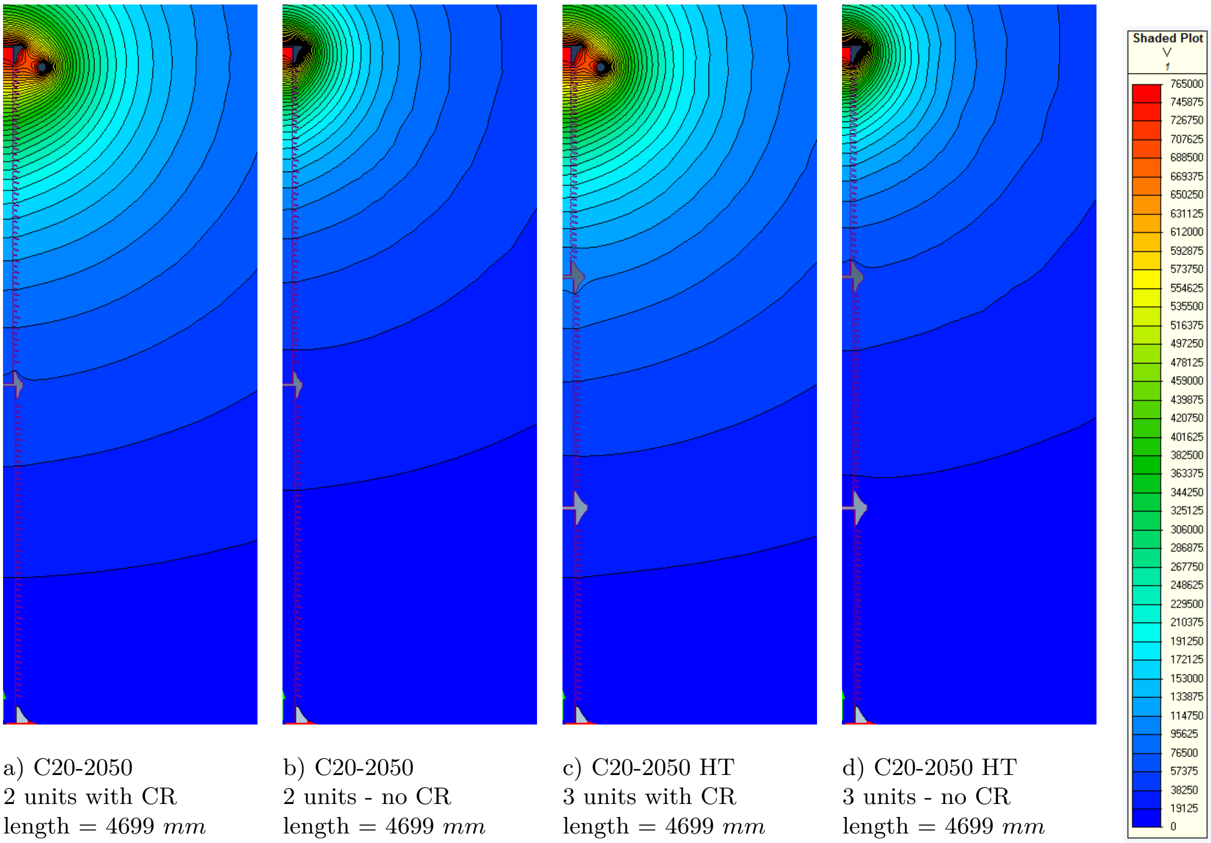
Figure 28 shows the simulated voltage characteristic of four out of five tested insulator arrangements with a dry lightning impulse withstand voltage of 2050 kV, test voltage was 765 kV. All the insulator arrangements have the same total hight of 4699 mm. Insulator 28a) consists of 2 units and has the latest advanced shed design (year 2009) with very thin alternating sheds and a creepage distance of about 11800 mm. Insulator b) is the same as shown in a) but has no corona ring. The insulator design (year 2007) seen in c) also consists of 2 units but has more spacing between the sheds and a creepage distance of about 11900 mm. Insulator d) is the same as shown in c) but has no corona ring. Also simulated but not displayed was an insulator arrangement with 6 units and an creepage distance of about 10400 mm, it was produced by a competing company (year 1970).

Figure 29 shows a comparison of the combined field intensity and voltage characteristic plot of the top section of each insulator arrangement. The contour plot represents the voltage characteristic previously shown in figure 28. The shaded plot represents the field intensity standardized to a maximum value of $4 \cdot 10^6 kV/mm$. Obvious hot spots are near rough edges of the top fitting and between the outermost and lowest point of the first sheds. The effect of the corona ring is also easily recognizable, the voltage characteristic is much more homogeneous over the radial section and the voltage decrease also is slower and linearised. In figure 29c) and d) the sheds close to the fitting stand out, the field intensity reaches really high values and therefore could be critical.

Figure 30 shows the graphs of the comparison of the field intensity for the various insulator arrangements. Graph a) shows the course of the electric field for the whole insulator along the outermost point of the shed, chart b) shows the first meter from the top. As seen in figure 29 this point holds the highest field intensity and is therefore critical for discharge or flashover. The highest field intensity can be measured at the first shed, it can be seen that the more space lies between the shed and the top fitting, the less the field intensity.

Figure 31 shows the graphs of the comparison of the voltage characteristic for the various insulator arrangements. Graph a) shows the voltage characteristic for the whole insulator arrangement along the outermost point of the shed, graph b) shows a more detailed view of the voltage characteristic along the first meter from the top.

As previously seen for insulators of the same total height, the graphs show that the more units an insulator arrangement has, the faster the voltage is decreasing. All Insulators with a corona ring have about the same voltage characteristic with a much slower decreasing voltage. Due to the direct relationship of the voltage with the field intensity this fact has a positive impact on the



a) C20-2050
2 units with CR
length = 4699 mm

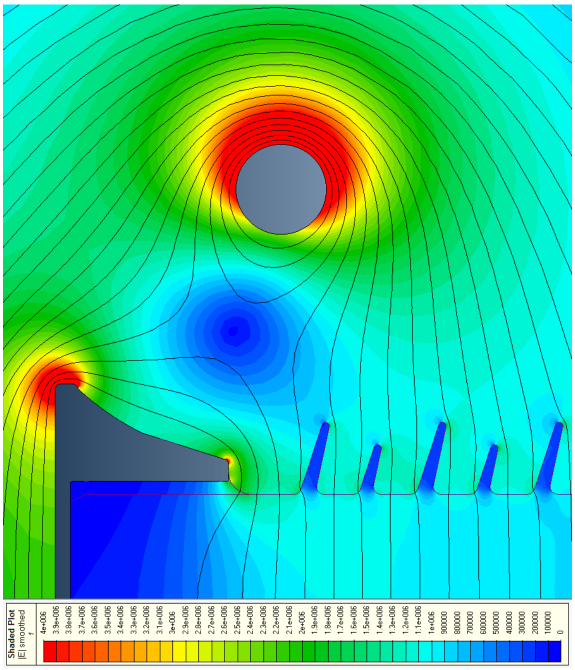
b) C20-2050
2 units - no CR
length = 4699 mm

c) C20-2050 HT
3 units with CR
length = 4699 mm

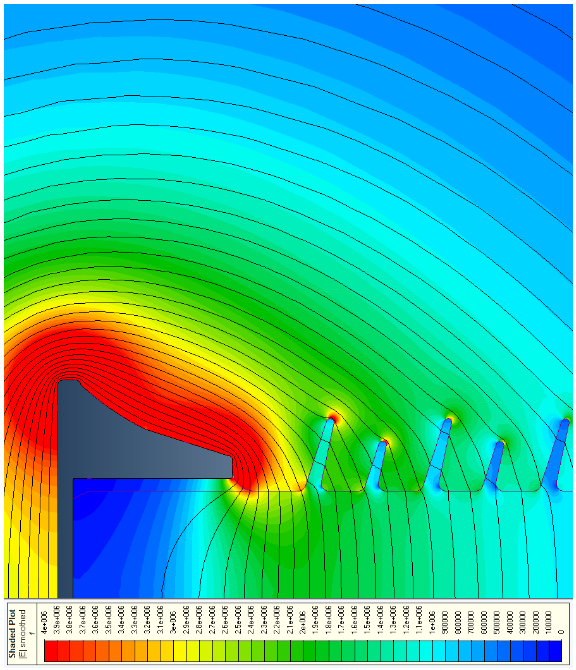
d) C20-2050 HT
3 units - no CR
length = 4699 mm

Fig. 28: Comparison of the voltage characteristic for various insulator arrangements for BIL2050 - total insulation arrangement

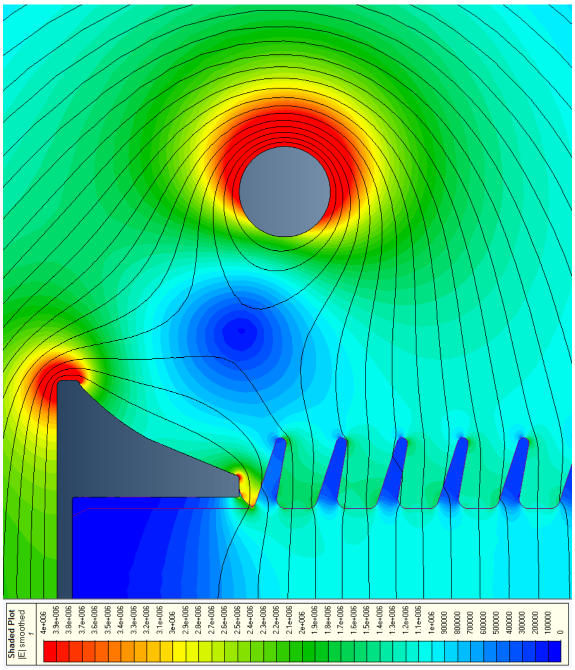
field intensity, the highest field intensity on the sheds does not exceed a value of $1.7 \cdot 10^6 kV/mm$. On the other hand insulators without a corona ring by far exceed the critical flashover value of $3 \cdot 10^6 kV/mm$ for air.



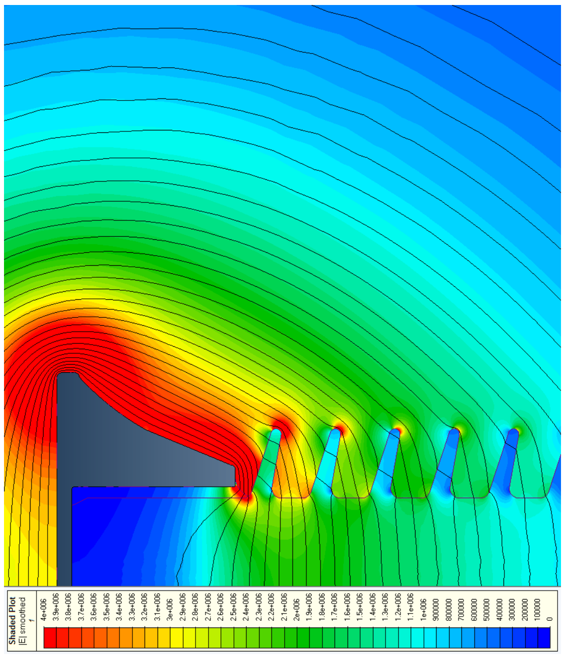
a) BIL C20-2050 - 2 units with CR - l = 4699 mm



b) BIL C20-2050 - 2 units - no CR - l = 4699 mm

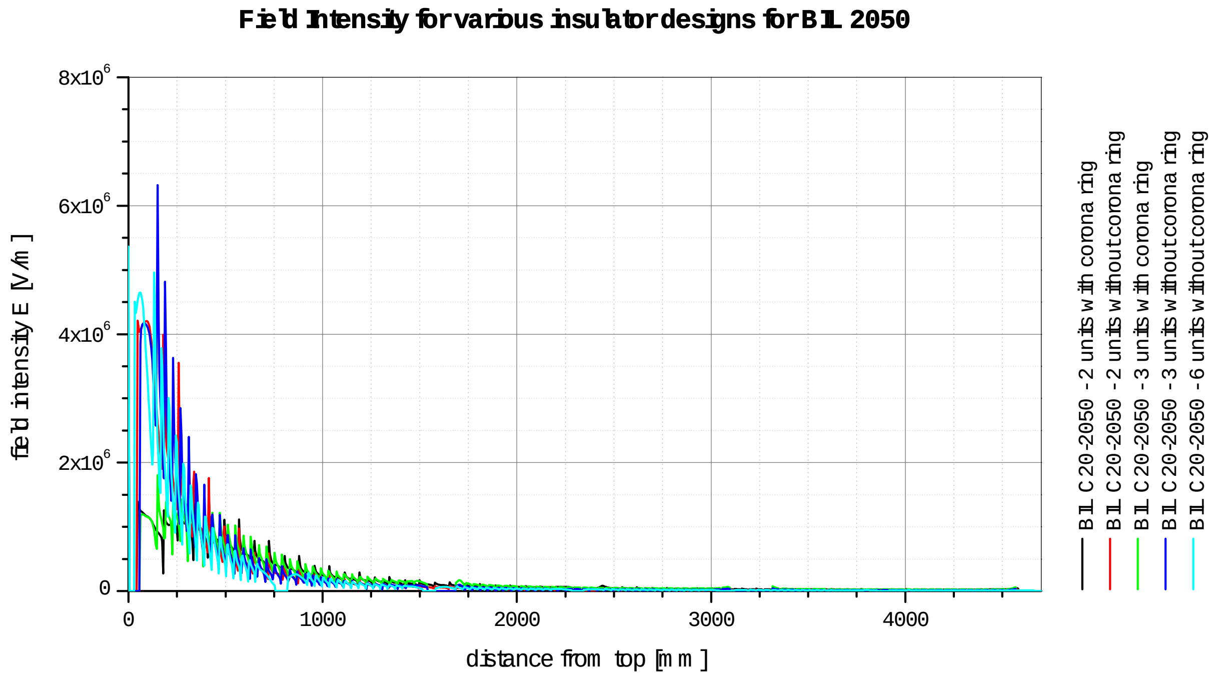


c) BIL C20-2050 HT - 3 units with CR - l = 4699 mm

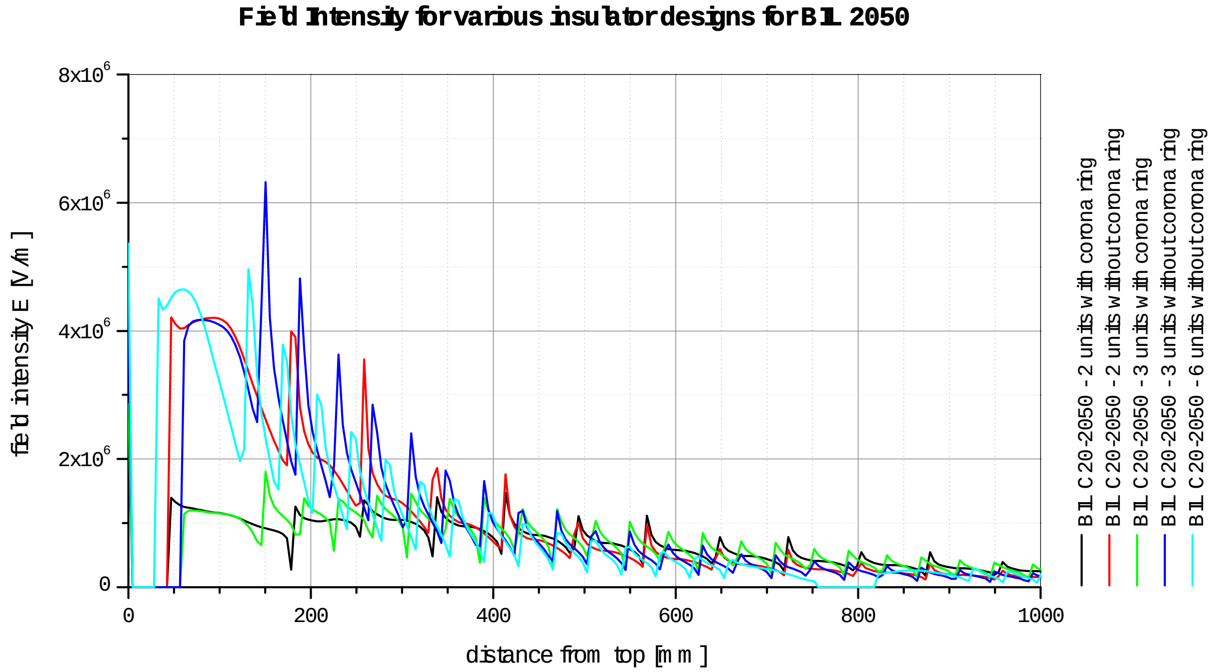


d) BIL C20-2050 HT - 3 units - no CR - l = 4699 mm

Fig. 29: Comparison of the field intensity and voltage characteristic for various insulator arrangements for BIL2050 - detailed view of the top fitting

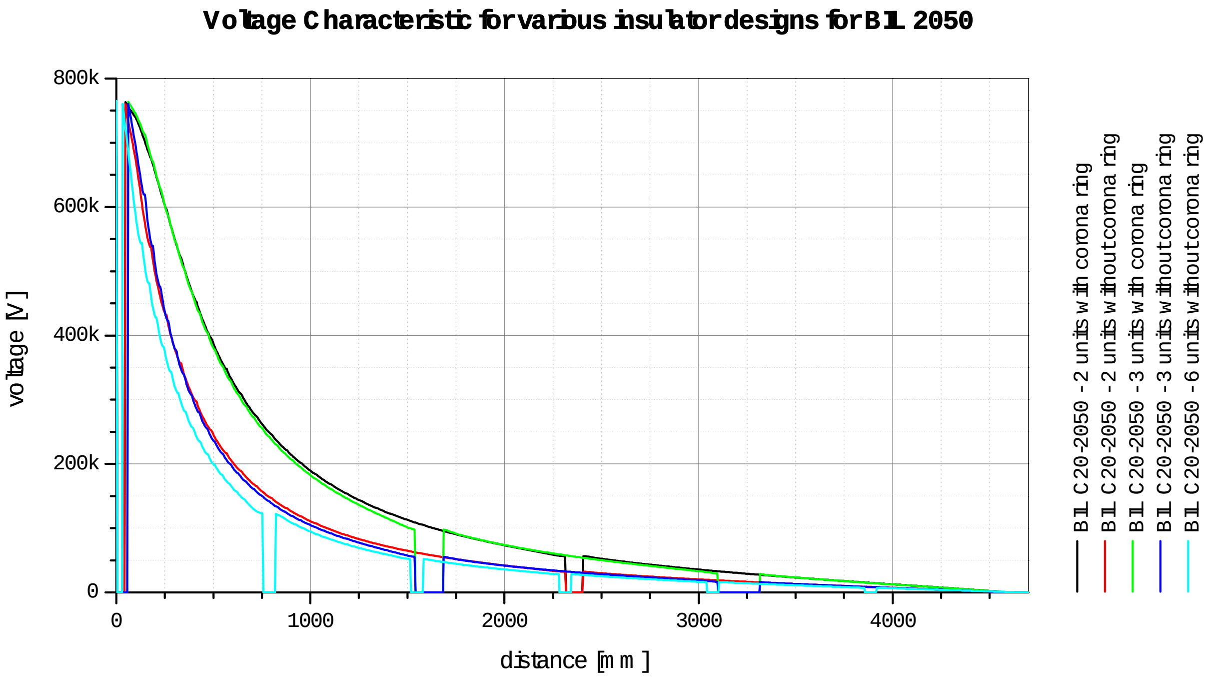


a) Course of the electric field for the whole insulator along the outer shed

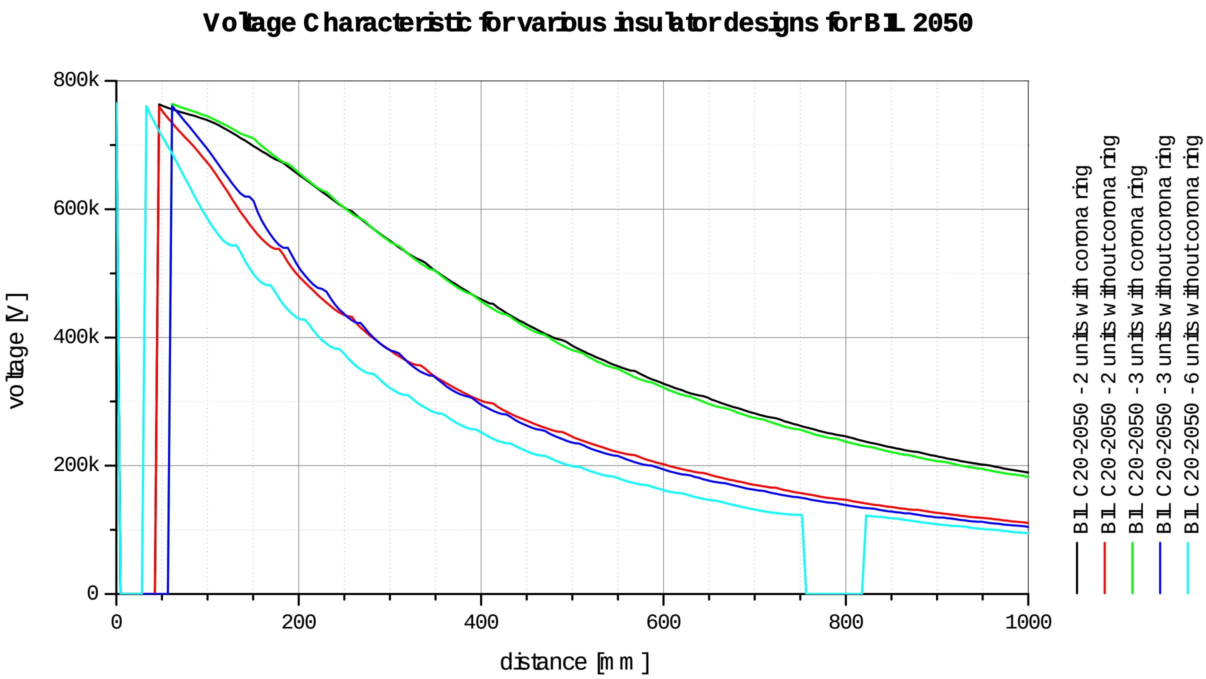


b) Course of the electric field for the first meter from the top along the outer shed

Fig. 30: Comparison of the field intensity for various insulator arrangements at BIL2050



a) Voltage Characteristic for the whole insulator along the outer shed



b) Voltage Characteristic for the first meter from the top along the outer shed

Fig. 31: Comparison of the voltage characteristic for various insulator arrangements at BIL2050

5.4 Comparison of the electrostatic field simulations for BIL 2550 insulators

Figures 32 and 33 show the simulated voltage characteristic of the eight tested insulator arrangements with a dry lightning impulse withstand voltage of 2550 kV, test voltage was 800 kV. All the insulator arrangements have the same total height of 5700 mm. Insulator 32a) consists of 2 units and has the latest advanced shed design (year 2009) with very thin alternating sheds and a creepage distance of about 20300 mm. Insulator b) is the same as shown in a) but has no corona ring. Insulator c) consists of 3 units, also has an advanced alternating shed design (year 2006) and a creepage distance of about 20700 mm. Insulator d) is the same as shown in c) but has no corona ring.

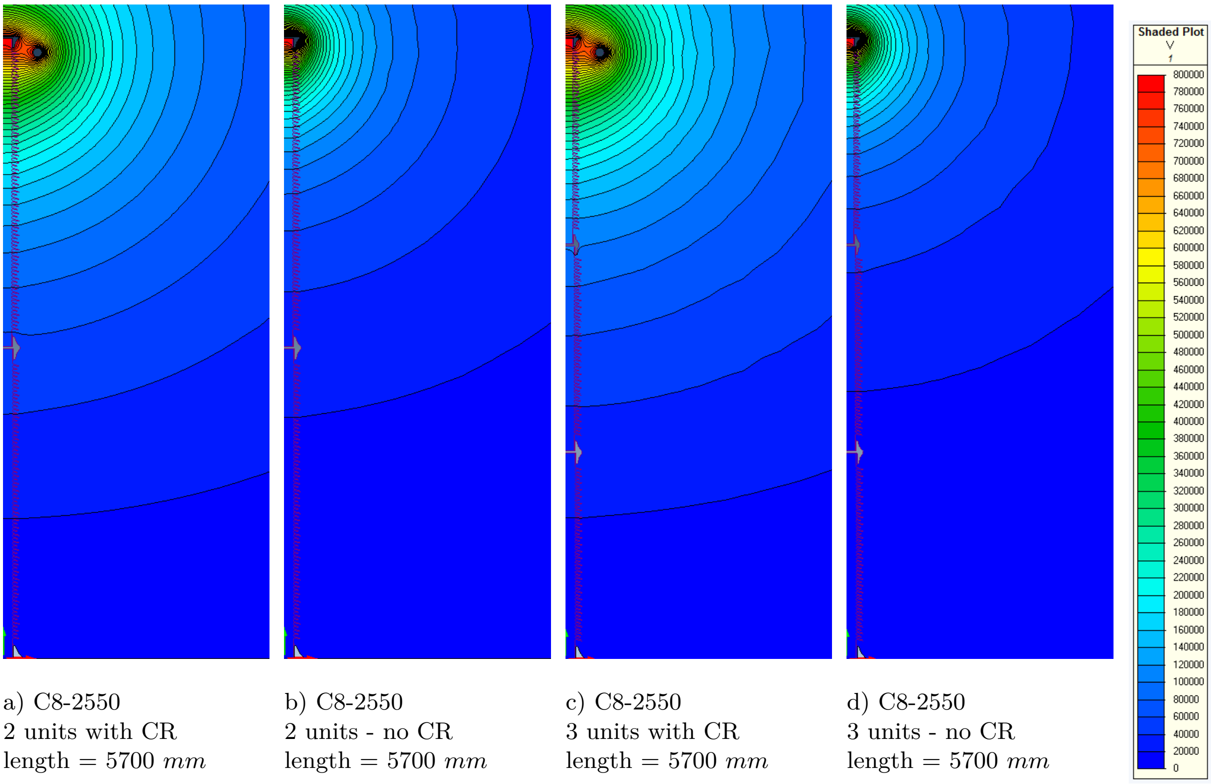
Insulator 33a) also consists of 3 units but has a higher bending load. Insulator b) is the same as shown in a) but has no corona ring. Insulator c) consists of 5 units with an older shed design (year 1970) and a creepage distance of about 9800 mm, no corona ring is attached. Insulator d) is also a 5 unit insulator with an older shed design but has a shed overhang of 45 mm instead of 40 mm and a creepage distance of about 10300 mm.

Figures 34 and 35 show a comparison of the combined field intensity and voltage characteristic plot of the top section of each insulator arrangement. The contour plot represents the voltage characteristic previously shown in figure 32. The shaded plot represents the field intensity standardized to a maximum value of $4 \cdot 10^6 kV/mm$. Obvious hot spots are near rough edges of the top fitting and between the outermost and lowest point of the first sheds, closest to the energized side of the insulator.

The effect of the corona ring is also clearly visible, the voltage characteristic is much more homogeneous over the radial section and the voltage decrease also is slower and linearised. Due to the high system voltage for insulators without a corona ring the field intensity has critically high values around the top fitting. And the first sheds of the insulator are again under great stress.

Figure 36 shows the graphs of the comparison of the field intensity for the various insulator arrangements. Graph a) shows the course of the electric field for the whole insulator along the outermost point of the shed, chart b) shows the first meter of the energized side of the insulator. As seen in figures 24 and 25 this point holds the highest field intensity and is therefore critical for discharge or flashover. The highest field intensity can be measured at the first shed, it can be seen that the more space lies between the shed and the top fitting, the less the field intensity.

Figure 37 shows the graphs of the comparison of the voltage characteristic for the various insulator arrangements. Graph a) shows the voltage characteristic for the whole insulator ar-



a) C8-2550
2 units with CR
length = 5700 mm

b) C8-2550
2 units - no CR
length = 5700 mm

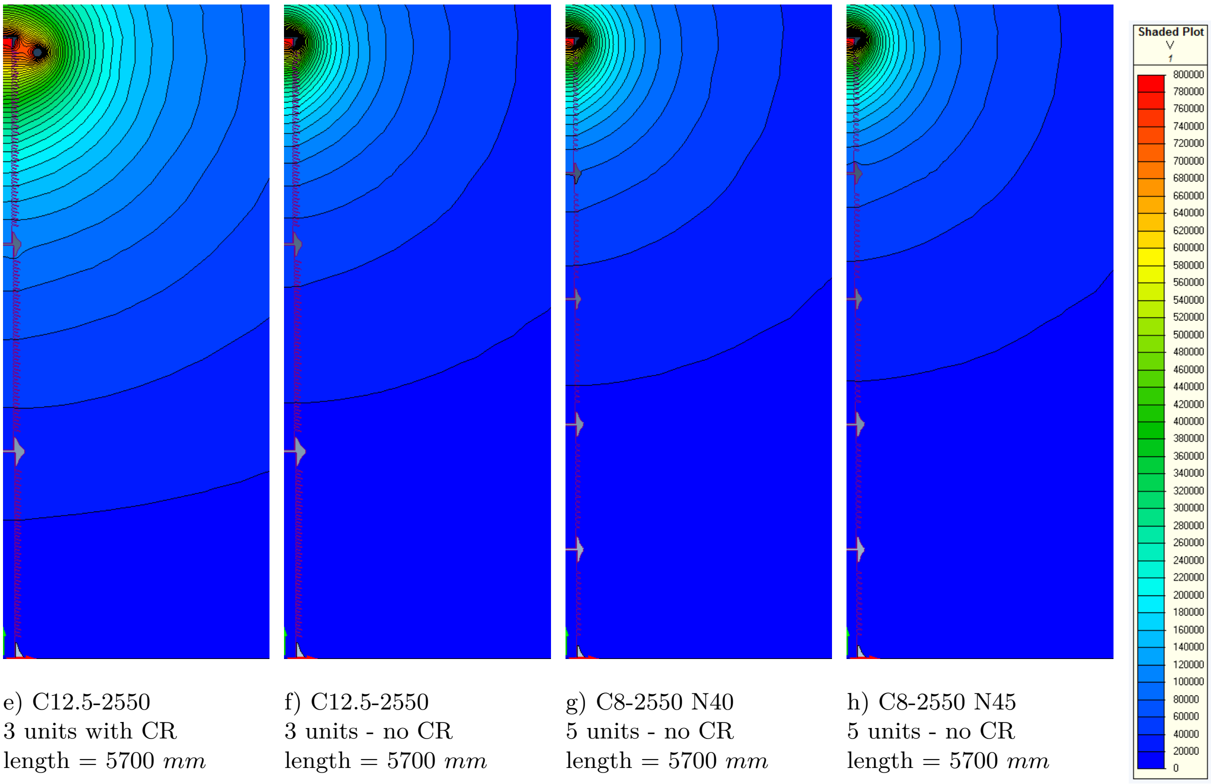
c) C8-2550
3 units with CR
length = 5700 mm

d) C8-2550
3 units - no CR
length = 5700 mm

Fig. 32: Comparison of the voltage characteristic for various insulator arrangements for BIL2550 - part 1 - total insulation arrangement

rangement along the outermost point of the shed, graph b) shows a more detailed view of the voltage characteristic along the first meter of the energized side of the insulator.

As previously noted, the graphs compare insulators of the same total height and show, that more single insulation units in an insulator arrangement cause a faster voltage decrease. What's new is the effect of the shed overhang. The 5 unit insulators have the same number of sheds, the same spacing and fitting. The insulator with the higher overhang has a slightly greater but noticeable voltage decrease. All Insulators with a corona ring have about the same voltage characteristic with a much slower decreasing voltage. Due to the direct relationship of the voltage with the field intensity this fact has a positive impact on the field intensity. As seen in figure 36 for insulators with a corona ring the highest field intensity on the sheds does not exceed a value of $1.2 \cdot 10^6 kV/mm$. On the other hand insulators without a corona ring by far exceed the critical flashover value of $3 \cdot 10^6 kV/mm$ for air.



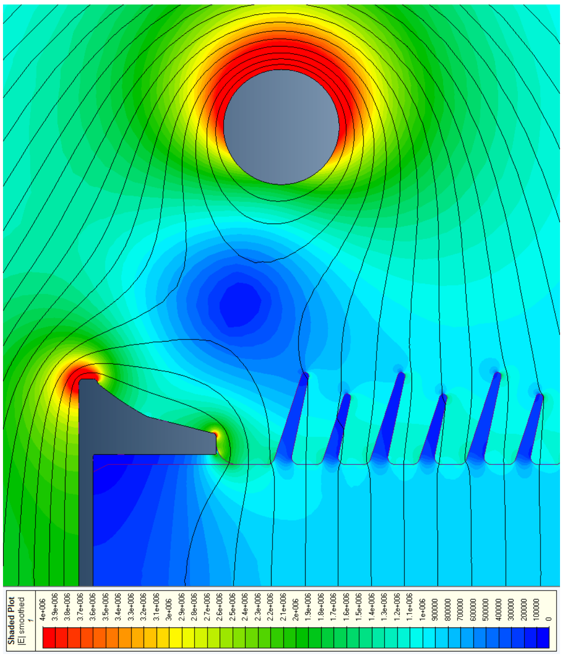
e) C12.5-2550
3 units with CR
length = 5700 mm

f) C12.5-2550
3 units - no CR
length = 5700 mm

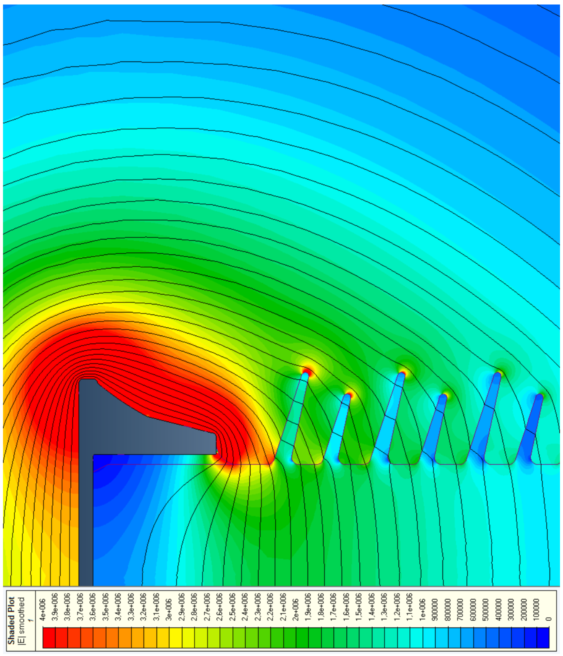
g) C8-2550 N40
5 units - no CR
length = 5700 mm

h) C8-2550 N45
5 units - no CR
length = 5700 mm

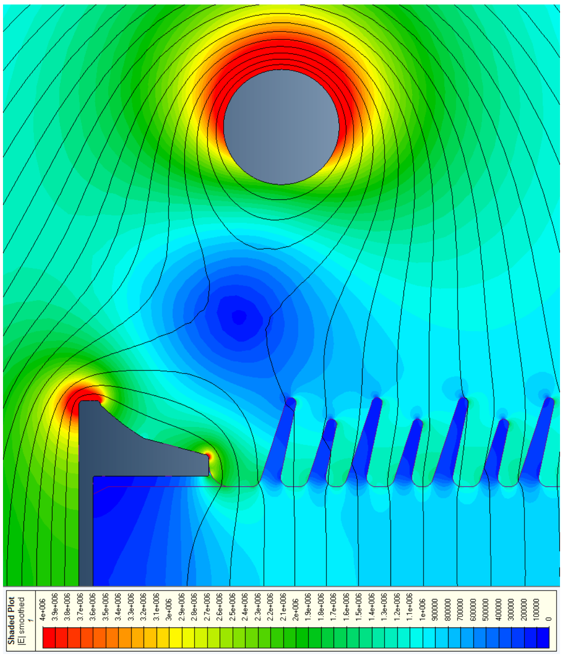
Fig. 33: Comparison of the voltage characteristic for various insulator arrangements for BIL2550 - part 2 - total insulation arrangement



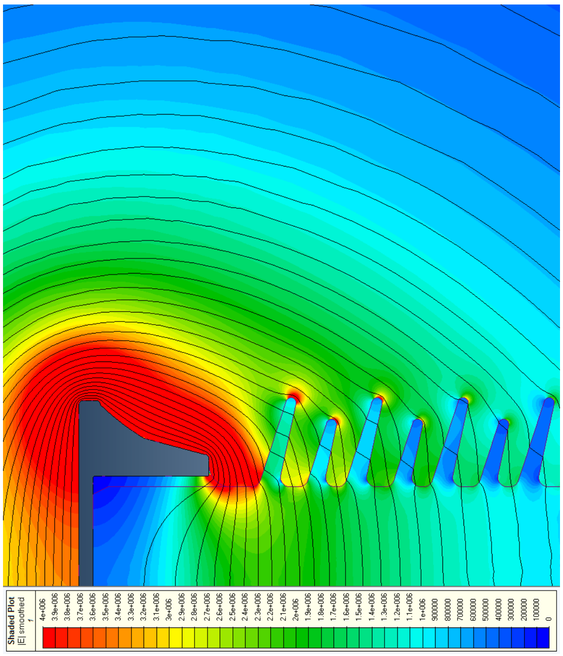
a) BIL C8-2550 - 2 units with CR - l = 5700 mm



b) BIL C8-2550 - 2 units - no CR - l = 5700 mm

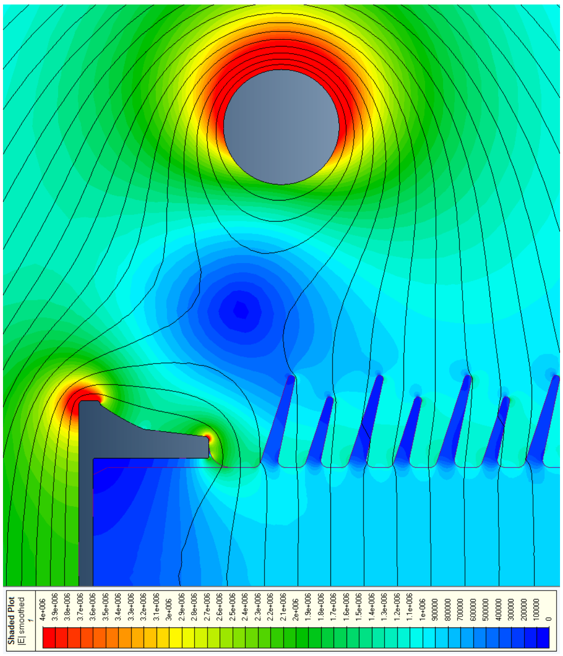


a) BIL C8-2550 - 3 units with CR - l = 5700 mm

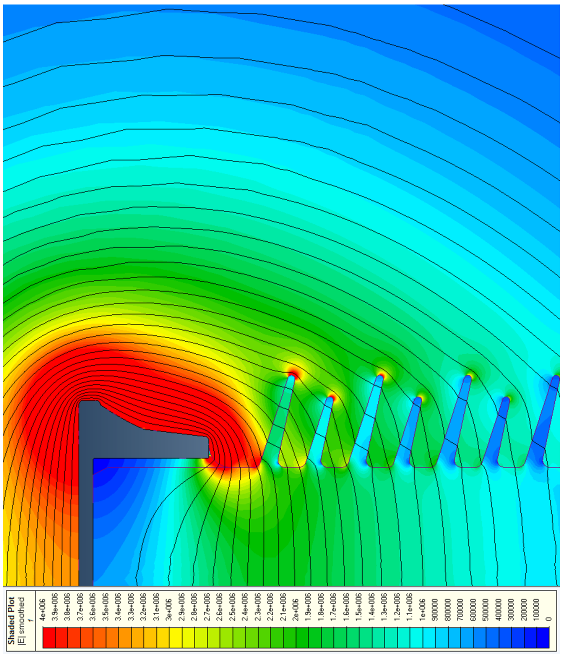


b) BIL C8-2550 - 3 units - no CR - l = 5700 mm

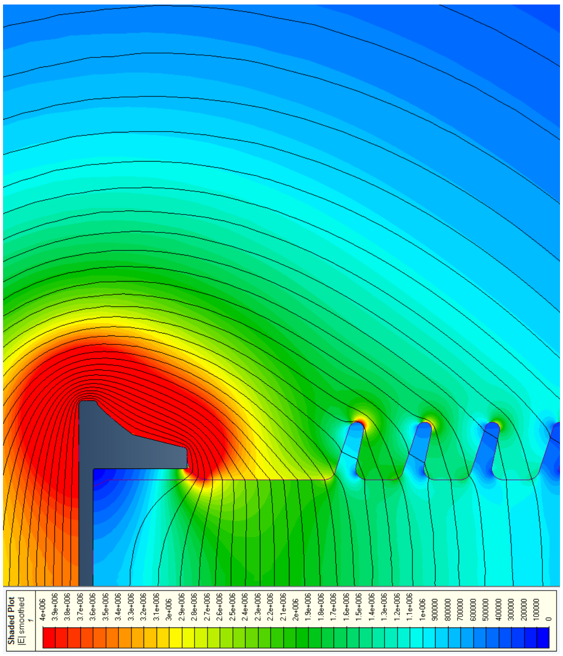
Fig. 34: Comparison of the field intensity and voltage characteristic for various insulator arrangements for BIL2550 - part 1 - detailed view of the top fitting



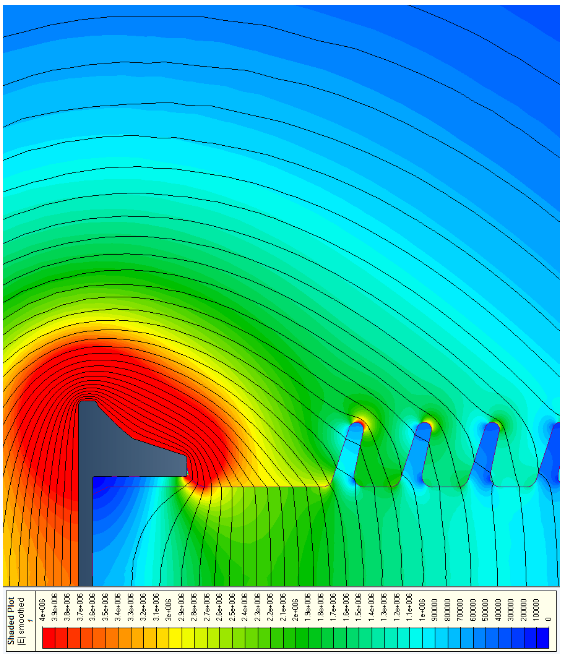
c) BIL C12.5-2550 - 3 units with CR - l = 5700 mm



d) BIL C12.5-2550 - 3 units - no CR - l = 5700 mm

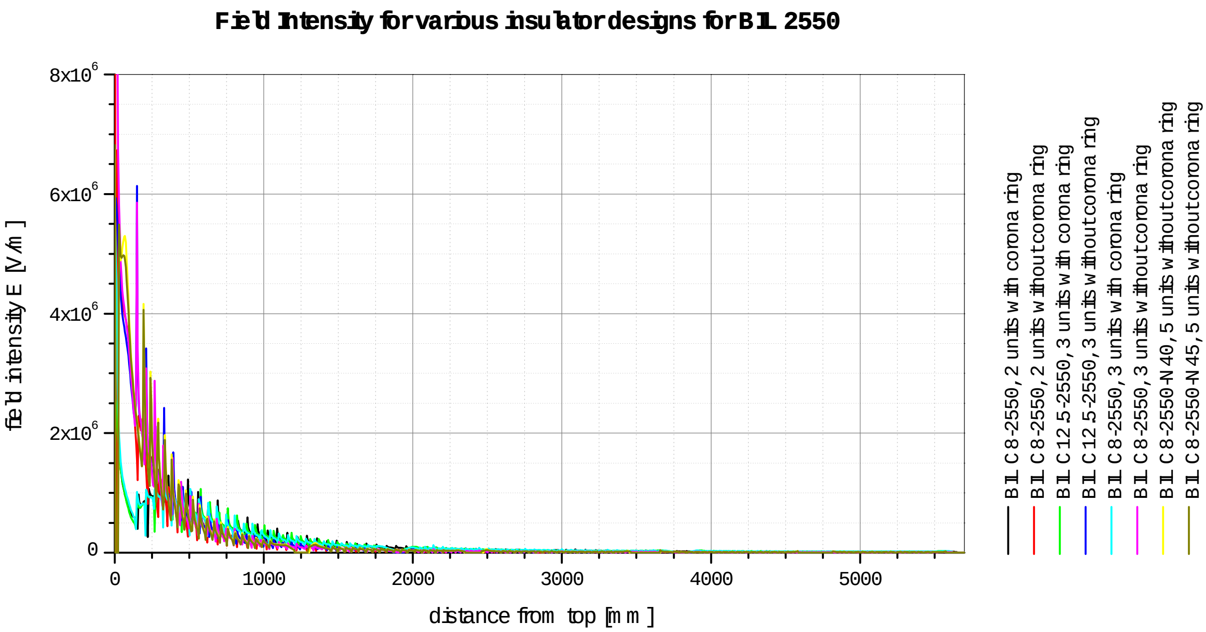


c) BIL C8-2550-N40 - 5 units - no CR - l = 5700 mm

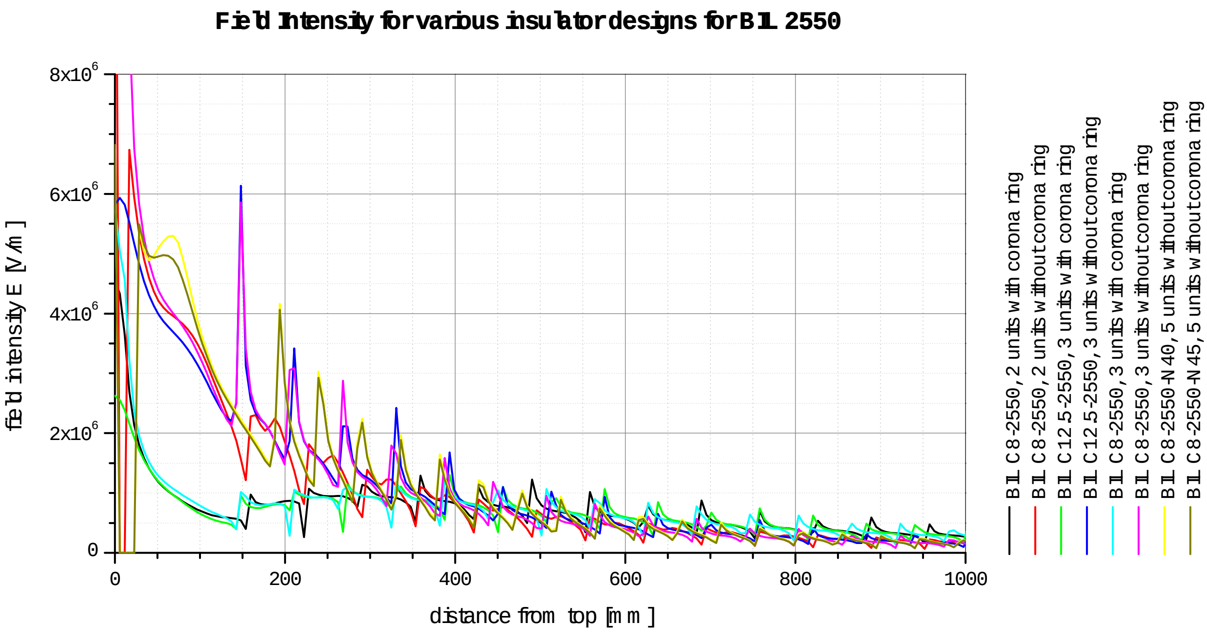


d) BIL C8-2550-N45 - 5 units - no CR - l = 5700 mm

Fig. 35: Comparison of the field intensity and voltage characteristic for various insulator arrangements for BIL2550 - part 2 - detailed view of the top fitting

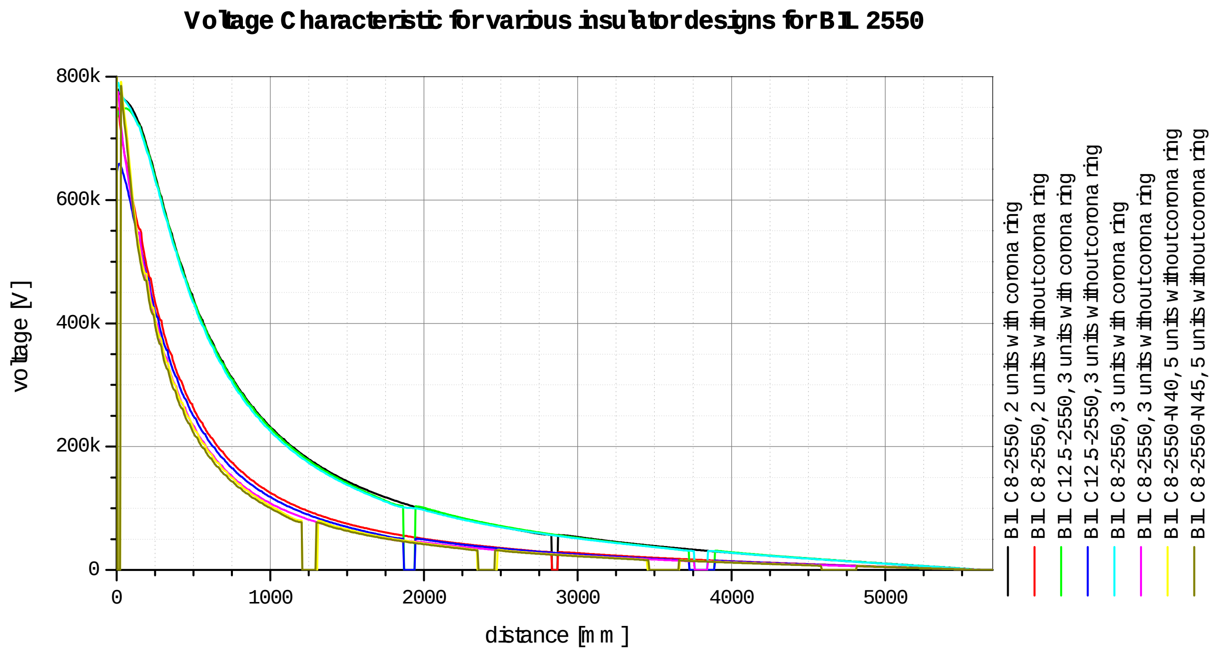


a) Course of the electric field for the whole insulator along the outer shed

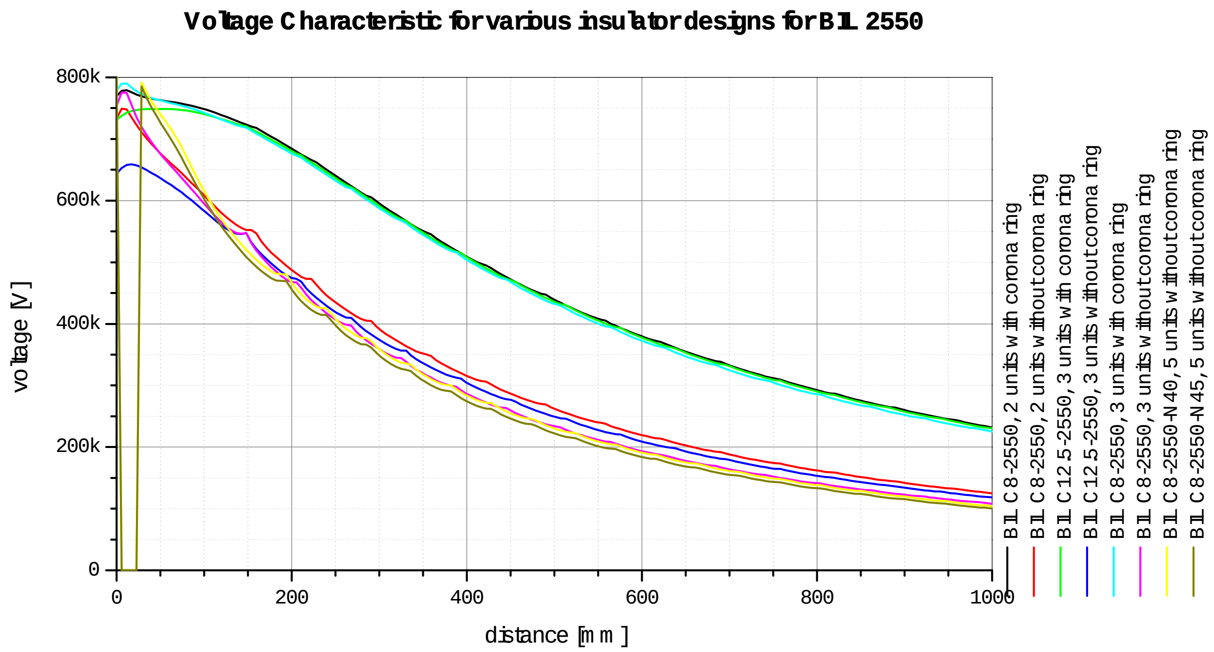


b) Course of the electric field for the first meter from the top along the outer shed

Fig. 36: Comparison of the field intensity for various insulator arrangements at BIL2550



a) Voltage Characteristic for the whole insulator along the outer shed



b) Voltage Characteristic for the first meter from the top along the outer shed

Fig. 37: Comparison of the voltage characteristic for various insulator arrangements at BIL2550

5.5 Discussion of the results

This section summarizes the findings provided with the studies described in this chapter. The electrostatic field simulations have shown some interesting behaviour concerning the effects of the insulator profile on the field intensity and voltage characteristics:

Stray capacities around the fittings badly affect the electric field distribution which influence the reliability of the system operation. The electric field stress is several times higher at the energized end of the insulator, compared to the middle or near ground. Similar observations have been made in another investigation [54].

The voltage characteristic of the insulator arrangement was clearly affected by the number of single insulation units. All simulations showed the same results, the more units an insulator has, the faster the voltage decreases along the whole insulator, especially along the first critical sheds of the insulator. The decreasing voltage is inversely proportional to the field intensity but therefore reaches higher values at the first sheds. The discontinuities in the field intensity graphs refer to boundary layers, caused by a different permittivity of the model material.

The position of the sheds close to the fitting holding the system voltage have a great impact on the highest field intensity. The closer the shed is to the fitting, the higher the maximum field intensity. The shed overhang has also an effect on the voltage characteristic of an insulator. If the overhang is higher, the voltage decrease along the outer shed is progressing more strongly and has, at a certain point, a negative effect on the field intensity.

All charts and graphs regarding the field simulations in this chapter show clearly that the part of the insulator holding the system voltage has the highest field intensity. It can be measured near the outermost and lowest point of the sheds close to the energized end of the insulator, depending whether a corona ring was used or not. Especially the first sheds are under great stress.

By using field regulating measures, like a corona ring, these high field intensities can be reduced. Insulators assembled with a corona ring have a much more homogeneous voltage characteristic in radial direction and a slower and linearised decreasing voltage characteristic. The field intensity along the first sheds is about four times smaller than the same insulator without a corona ring. Additionally its maximum is far from a critical value.

It seems the effect of a corona ring is more dominant on the voltage characteristic of an insulator than the number of single insulation units. All insulators with a corona ring have nearly the same voltage characteristic. It is still noticeable that insulators with more units have a faster decreasing voltage characteristic but the difference compared to insulators without a corona ring is much less.

6 Summary

Chapter 1 gives a quick overview of the application area of ceramic post-insulators. The central questions, that are answered in this chapter, include: What are the physical aspects? What are the material and electrical considerations? Which environmental factors have to be considered? And at last, how are station post insulators manufactured?

Chapter 2 gives an abstract of the IEC and ANSI standards, relevant for outdoor station-post-insulators of ceramic material with external metal fittings. Both IEC and ANSI standards define the total height, the creepage distance, the bending load, the lightning impulse voltage and the power frequency withstand voltage. The test procedures for electrical type tests are very similar for both the IEC and ANSI standards, as the ANSI test procedures are a slightly modified summary of the IEC test procedures. Both IEC and ANSI standards define values for a basic insulation level (BIL) of 1300 kV. The obvious difference between the IEC and ANSI standards is the requested total height (ANSI = 2692 mm, IEC = 2900 mm) and the creepage distance (ANSI = 5867 mm, IEC = 5100 mm and 7000 mm).

Due to the more sophisticated manufacturing process, single insulators with a lot greater height can be produced. Insulators have a more homogeneous and stronger material composition than 40 years ago. Furthermore the improved shed design of the latest insulators also brings a weight decrease of about 15-20% and an improved form factor of about 10% [16]. Relevant dimensional characteristics in the IEC and ANSI standard haven't changed in the last 40 years, although much higher single insulator units with better electrical characteristics are used today. A revision of both standards is long overdue. Replacing the requested total insulator height with the requested arcing distance would also be a better choice.

Chapter 3 describes the simulation software for the static electric field simulations. The static electric field simulations have been performed using the software ElecNet by Infolytica, which is a software based on finite element analysis methods to solve 2D/3D rotationally symmetric or plane-parallel static electric field problems. An integral part of this thesis, that required a lot of dedication, was writing the visual basic scripting code using a Microsoft Excel® macro, which automatically solves the static electric field for any insulator arrangement up to 6 units with a plain or alternating shed design. A field simulation with or without a corona ring is possible, as well as using different material characteristics. The input data is verified for errors and checked if they meet the IEC profile requirements.

Chapter 4 summarizes the results of 7 type tests according to IEC and ANSI standards, performed for four groups of insulators with a dry lightning impulse withstand voltage of 1300 kV, 1425 kV, 2050 kV and 2550 kV. Insulators with the same mechanical and electrical characteristics have been compared, with the difference in single insulator unit length. Focus was on a modified non-standard insulator for a BIL of 1425 kV. The single-insulator unit had a height of 2850 mm, instead of the standard insulator height of 3150 mm, reached with 2 or 3 insulator units. All insulators passed the type tests and exceeded the required electrical values, even the shorter non-standard version. The demand for a shorter non-standard insulator is proven to be valid.

Chapter 5 shows the results of the field simulations for 24 different insulator profiles for four groups of insulators with a dry lightning impulse withstand voltage of 1300 kV, 1425 kV, 2050 kV and 2550 kV. The simulations confirm the assumption that less insulator units, for a given total insulator height, have a positive effect on the voltage characteristic and field distribution, due to an increased arcing distance. The approach to make the arcing distance a relevant factor and not the total insulator height has been validated.

The voltage characteristic of the insulator arrangement was clearly affected by the number of single insulation units. All simulations showed the same results, the more units an insulator has, the faster the voltage decreases along the whole insulator, especially along the first critical sheds of the insulator. The decreasing voltage is inversely proportional to the field intensity but therefore reaches higher values at the first sheds.

The highest field intensity along the insulator surface can be measured near the outermost and lowest point of the sheds close to the energized end of the insulator. The position of the sheds close to the fitting holding the system voltage has a great impact on the highest field intensity. The closer the shed is to the fitting, the higher the maximum field intensity.

Insulators assembled with a corona ring have a much more homogeneous voltage characteristic in radial direction and a slower and linearised decreasing voltage characteristic. The field intensity along the first sheds is about four times smaller than for the same insulator without a corona ring. Additionally its maximum is far from a critical value.

It is confirmed that the modelling of some insulator dimensions is very critically affecting the E-field distribution and must be performed with high precision. Critical aspects are the shed profile, location of the shed nearest to the end fitting, as well as the shape and size of the end fitting, shape and position of the corona ring [55].

7 Outlook

Further findings for a more optimized insulator profile could become available through more extensive simulations. A fact that also needs to be taken into account is that the field simulations act on the assumption that the insulator surface is clean. A pollution layer could mess up some considerations. The current implementation of the Microsoft Excel® macro script arranges the sheds exactly between the fittings, meaning the distance from the core to the outermost point of the sheds is the same on both ends. An implementation for an out of center arrangement is planned, as well as a conical core with varying shed overhang:

- Comparing the same insulator design with varying shed thicknesses
- Comparing the same insulator design with varying shed angles
- Comparing the same insulator design with varying vertical shed offsets
- Simulating insulators with a cone shaped core and a constant outer diameter
- Simulating insulators with a cone shaped core and a constant shed overhang

As the static electric field simulations are solved based on a finite element analysis method a different approach for an optimized field distribution is also possible. It should be possible to define the requested field distribution along the insulator as input value and the solver gives the shed profile as output value.

8 Conclusion

The main question concerning this thesis was: Do insulators need to have the same total height as 40 years ago, even if there are less conducting parts, or is it possible to reduce the height, yet still achieve the same level of insulation? The answer based on the results of the type test in chapter 4 performed on C20-1425mod and the given field simulations in chapter 5 is yes, but only under certain conditions. The shed design is an essential part of the decision making process.

All charts and graphs regarding the field simulations in chapter 5 show clearly that the part of the insulator holding the system voltage has the highest field intensity. Especially the first sheds are under great stress. By using field regulating measures, like a corona ring, these high field intensities can be reduced.

The electrostatic field simulations have shown some interesting behaviour concerning how the insulator profile is affecting the field intensity and voltage characteristics. Although the simulations have no significance regarding partial discharge, they can be used to detect critical parts of the insulator arrangement where partial discharge could occur. Measures could be taken to reduce the field intensity, like changing the design or selecting other materials. A fact that also needs to be taken into account is that the field simulations act on the assumption that the insulator surface is clean. A pollution layer could mess up some considerations.

Although a shorter insulator length for the same insulation level is proven to be possible, due to the lack of test objects, a general recommendation cannot be given at this point. An optimized insulator arrangement is yet already an economic factor. Less insulators with an advanced shed profile have the advantage of less weight, a faster production, less parts to ship and less parts to assemble, meaning the whole procedure has economic benefits at every step.

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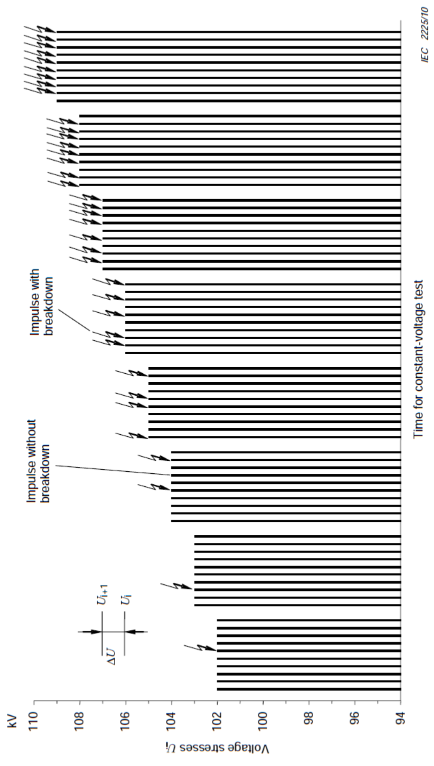
A Appendix

A.1 Multiple Level Test



number of voltage stress, i	1	2	3	4	5	6	7	8
number of voltage applications, n_i	10	10	10	10	10	10	10	10
number of disruptive discharges, k_i	1	1	2	4	5	7	8	9
disruptive-discharge frequency, $f_i = k_i/n_i$	0,1	0,1	0,2	0,4	0,5	0,7	0,8	0,9
total disruptive discharges, g	1	2	4	8	13	20	28	37

Figure A.1 – Example of a multiple-level (Class 1) test

Fig. 38: Example for the multiple level test [37]

A.2 Up-and-Down Test

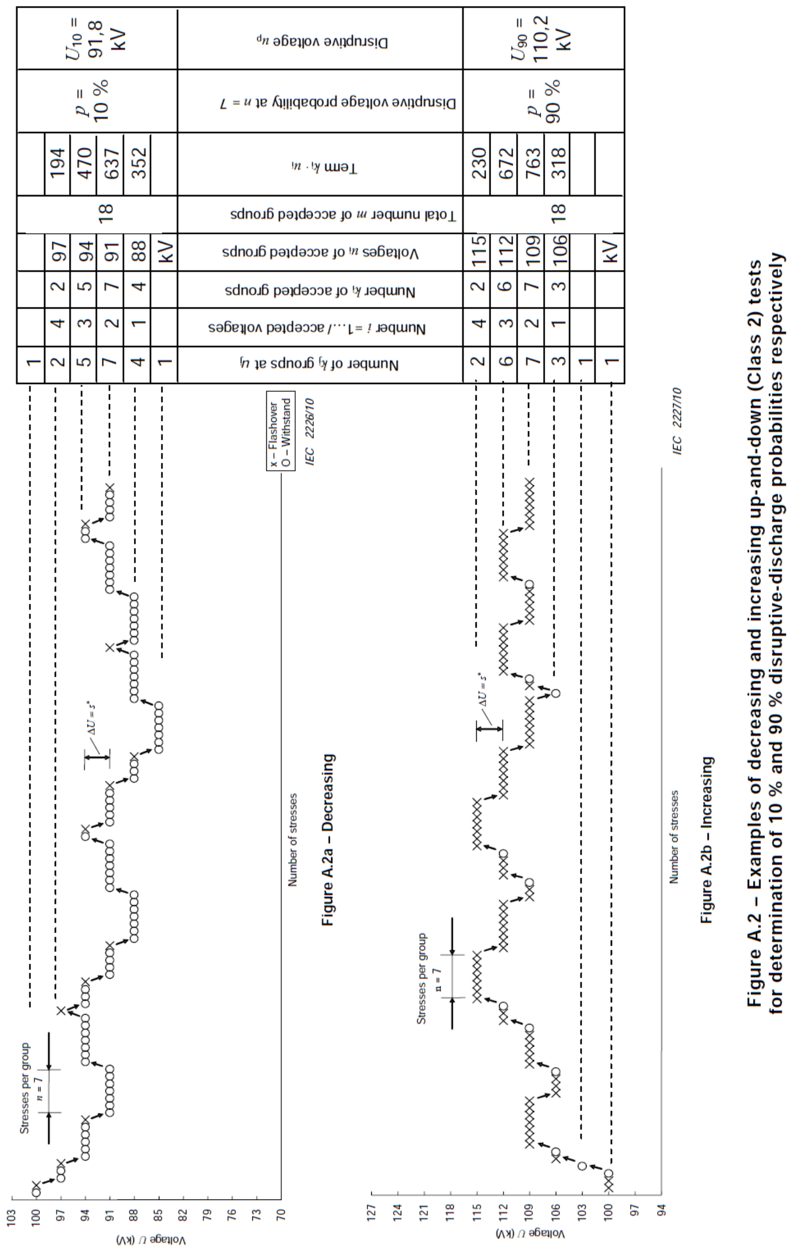
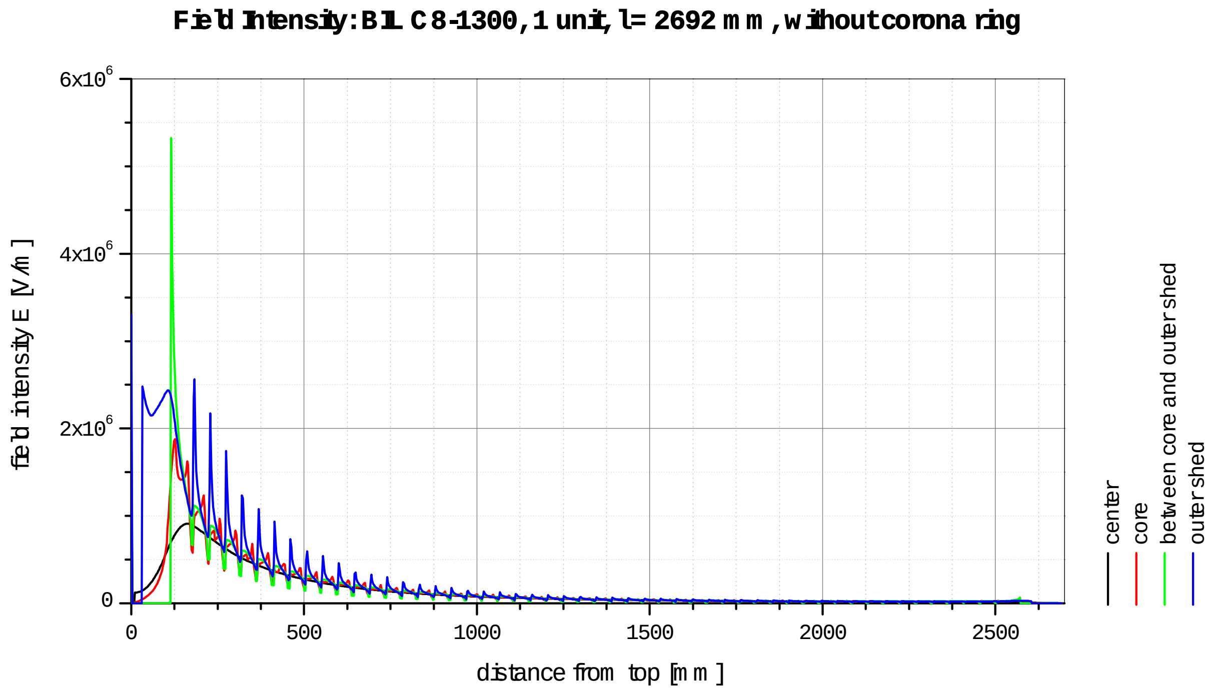


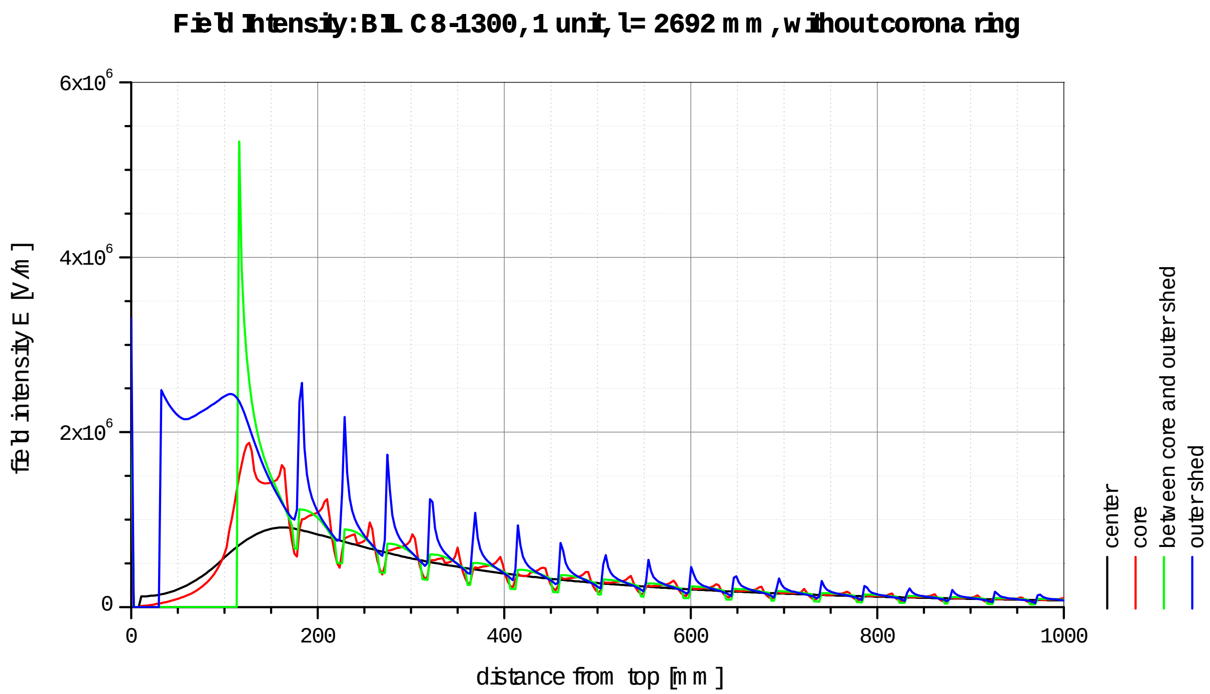
Fig. 39: Example for the up-and-down test [37]

A.3 Electrostatic Field Simualtions for BIL 1300 insulators

In the following section the results of the electrostatic field simulations for insulator arrangements with a dry lightning impulse withstand voltage of 1300 kV can be found. All arrangements have been simulated at a system voltage of 380 kV. The graphs show the progression of the field intensity and voltage characteristic of the single insulator arrangement at different radial lines across the whole insulator.

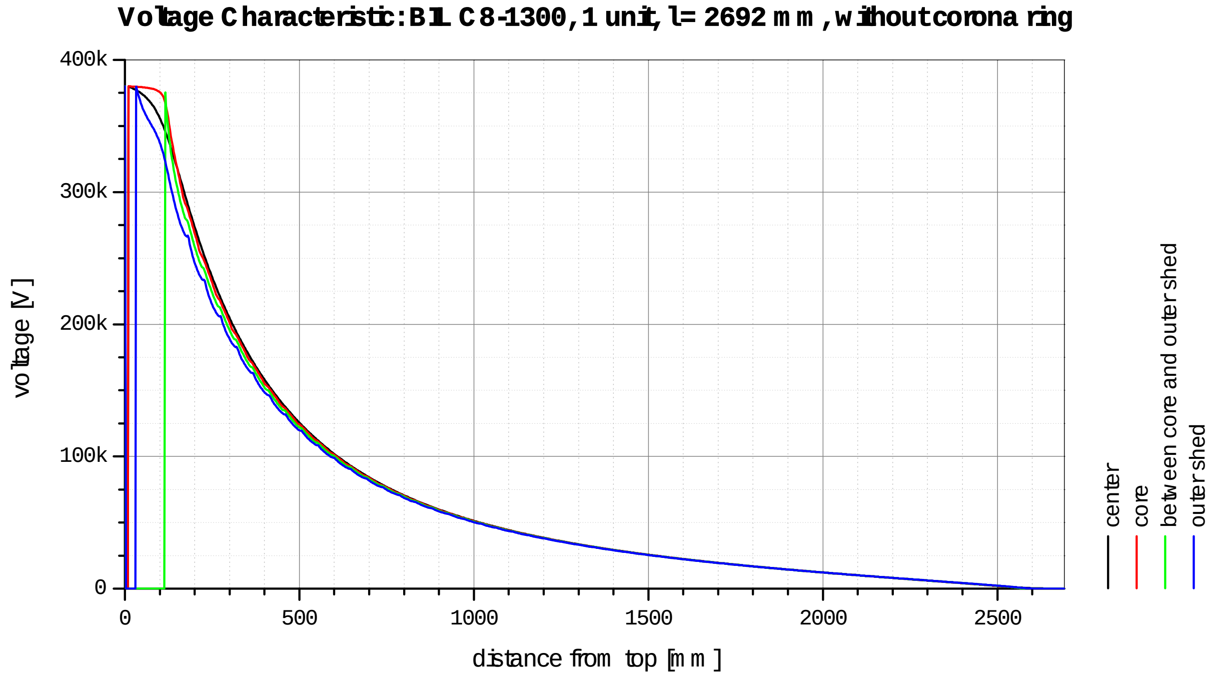


a) Course of the electric field along the whole insulator at different radial points

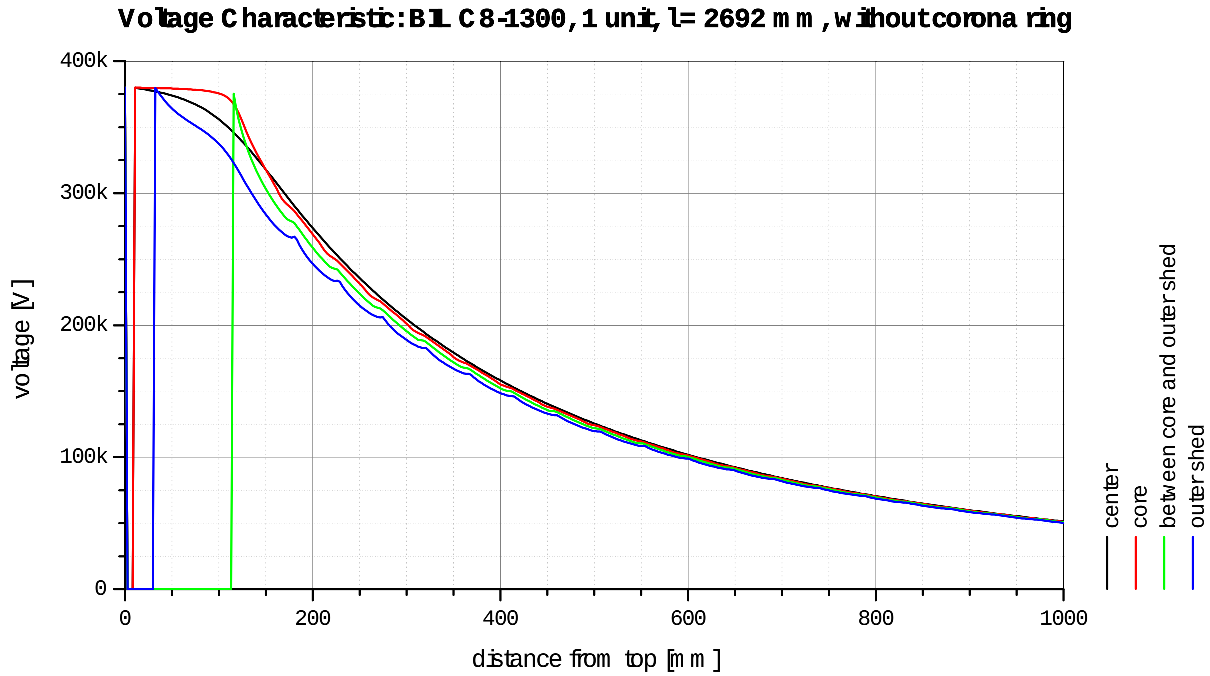


b) Course of the electric field along the first meter from the top at different radial points

Fig. 40: Field Intensity: BIL C8-1300, 1 units, l = 2692 mm, without CR

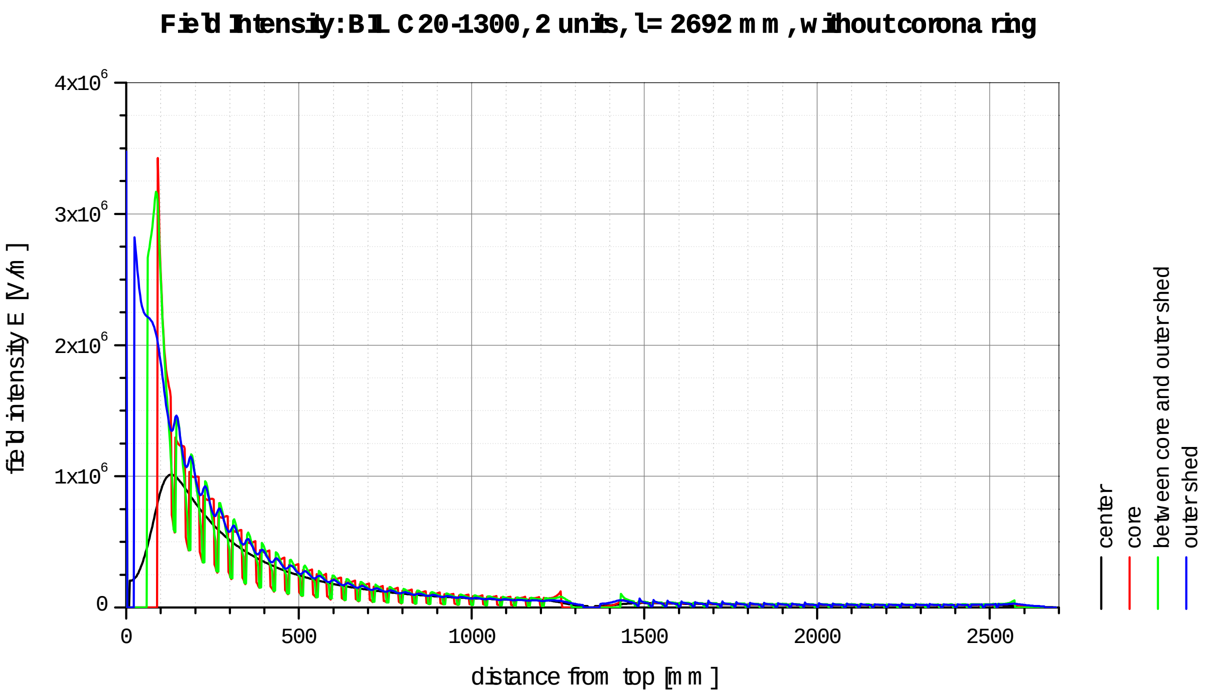


a) Voltage Characteristic along the whole insulator at different radial points

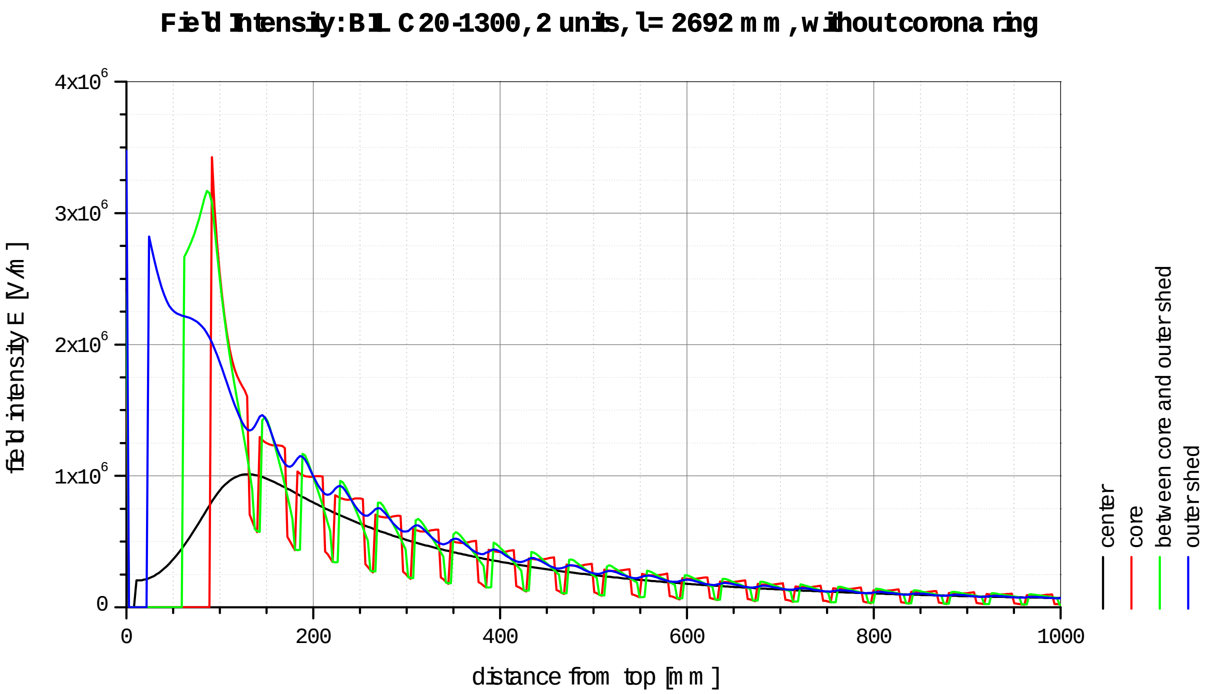


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 41: Voltage Characteristic: BIL C8-1300, 1 units, l = 2692 mm, without CR

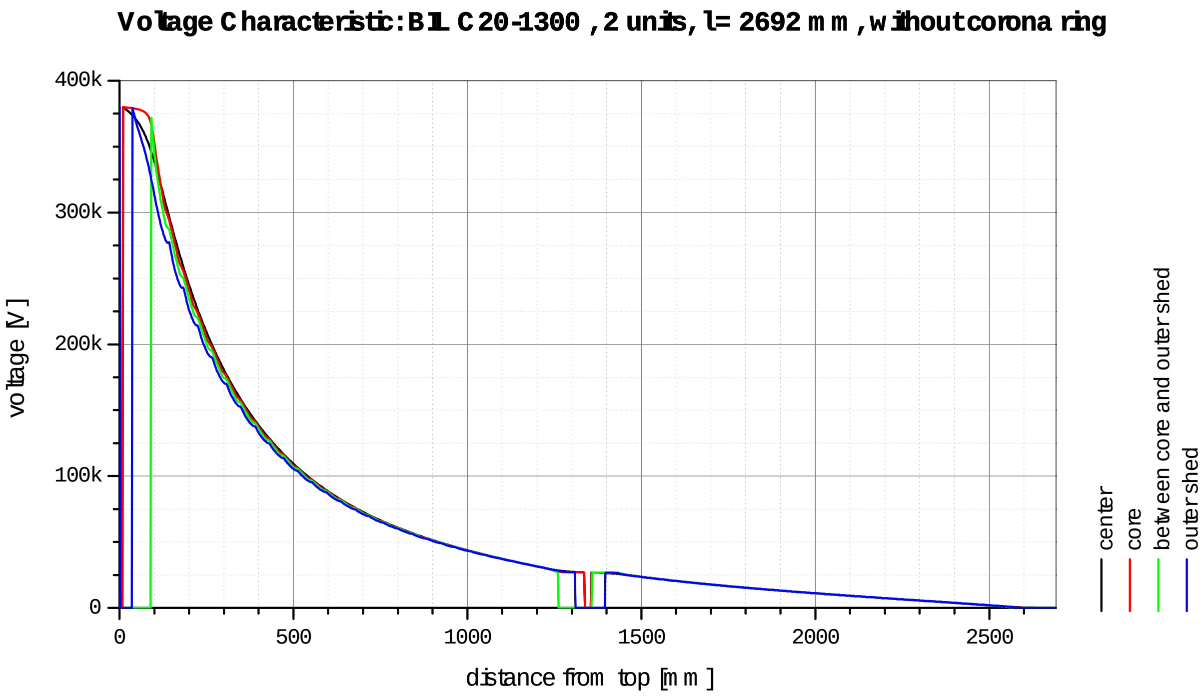


a) Course of the electric field along the whole insulator at different radial points

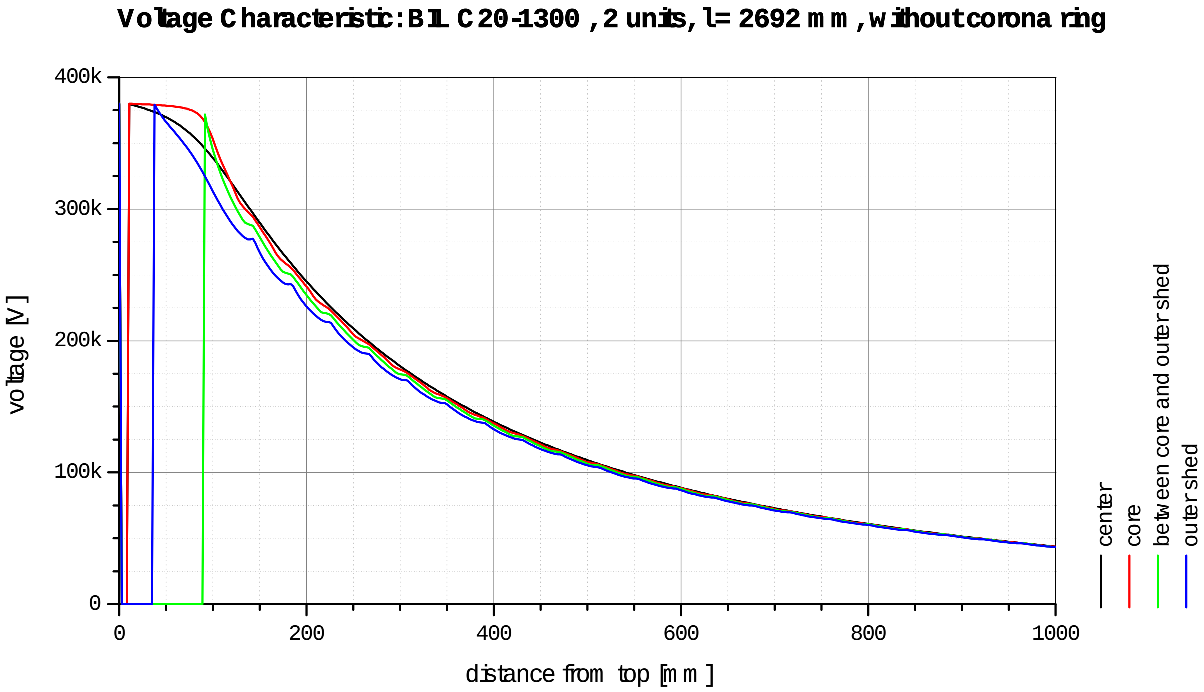


b) Course of the electric field along the first meter from the top at different radial points

Fig. 42: Field Intensity: BIL C20-1300, 2 units, l = 2692 mm, without CR

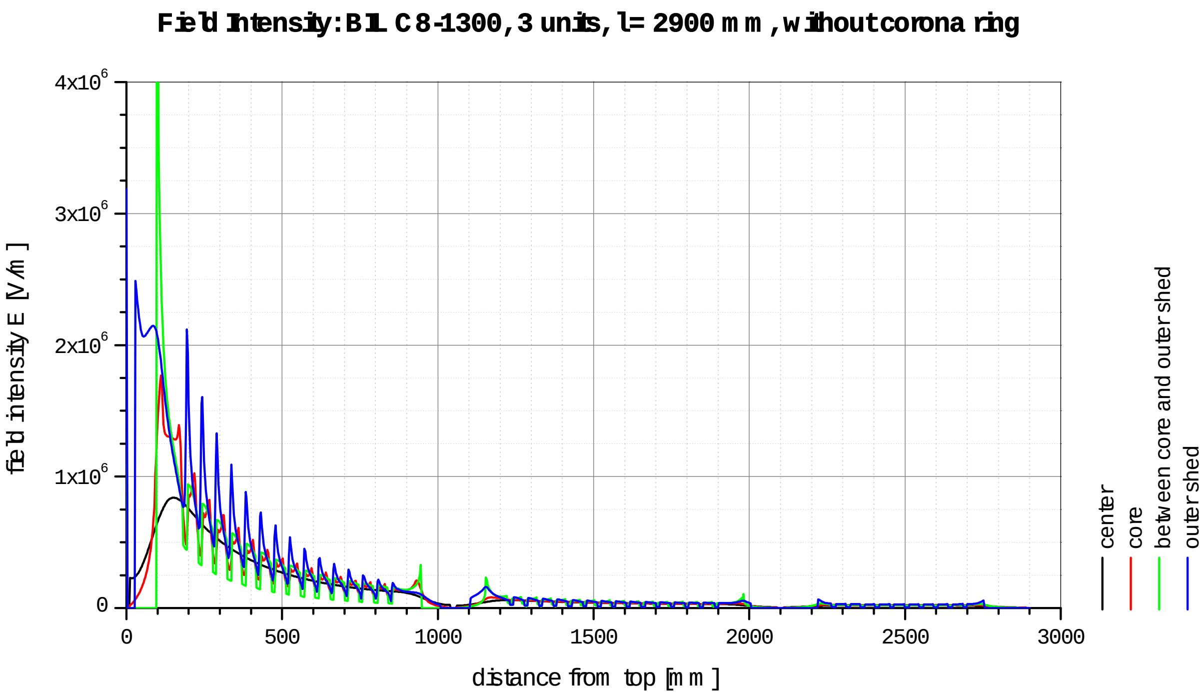


a) Voltage Characteristic along the whole insulator at different radial points

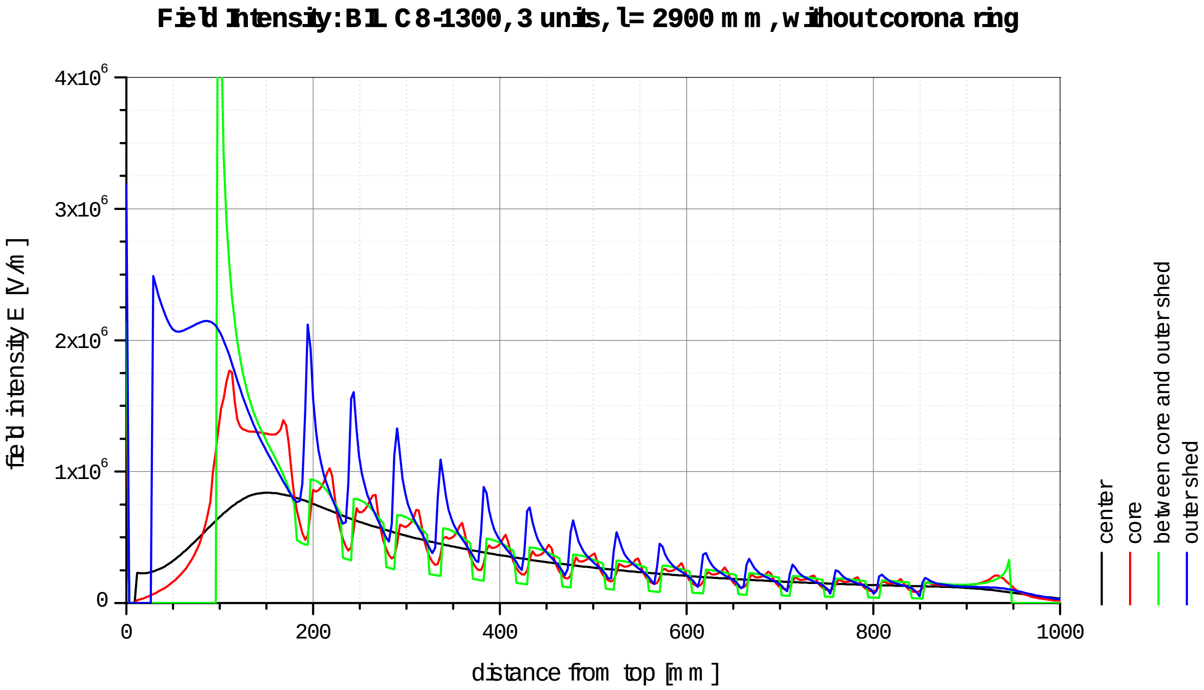


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 43: Voltage Characteristic: BIL C20-1300, 2 units, l = 2692 mm, without CR

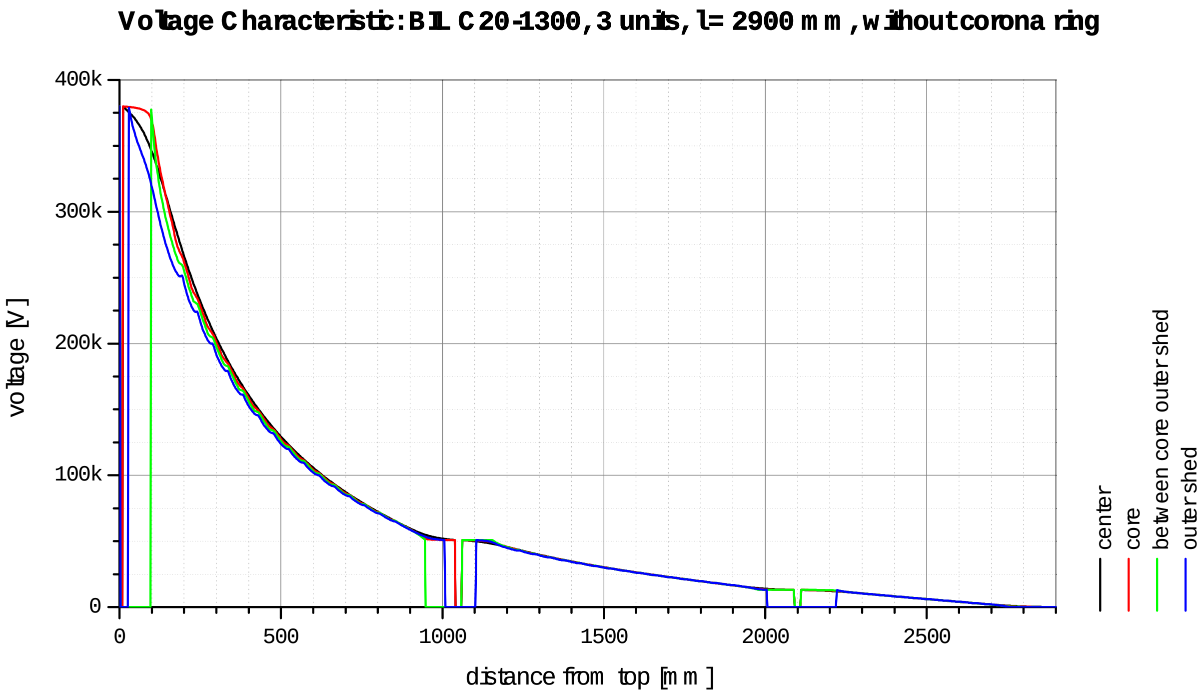


a) Course of the electric field along the whole insulator at different radial points

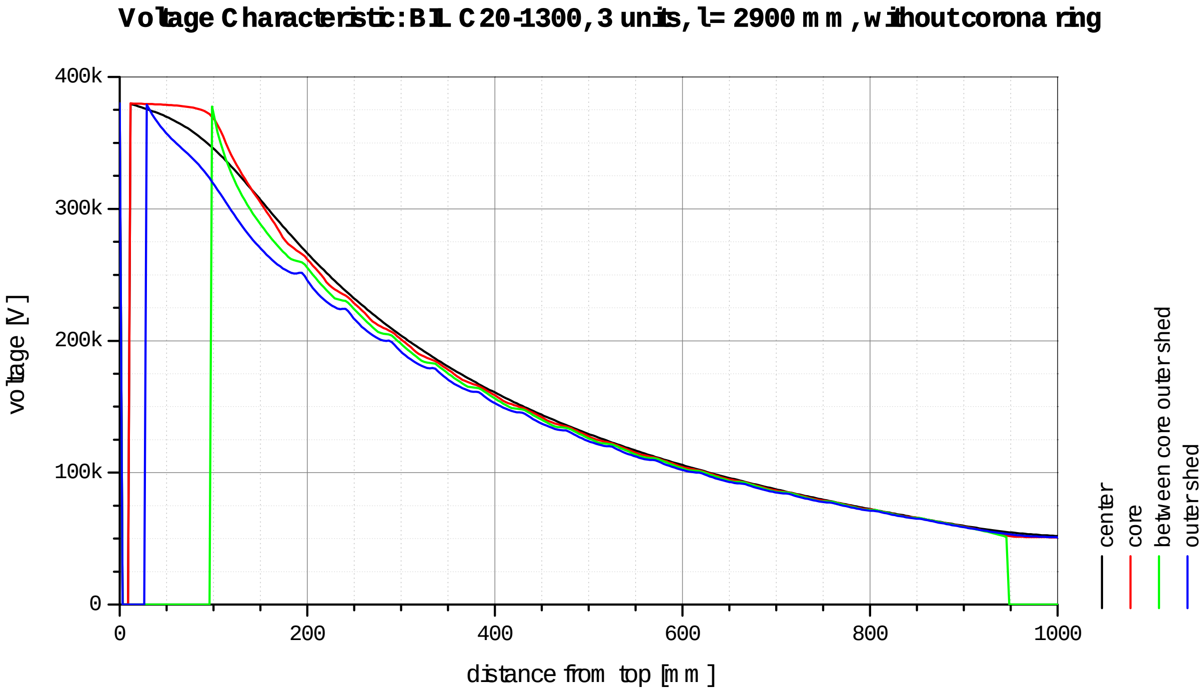


b) Course of the electric field along the first meter from the top at different radial points

Fig. 44: Field Intensity: BIL C8-1300, 3 units, l = 2900 mm, without CR

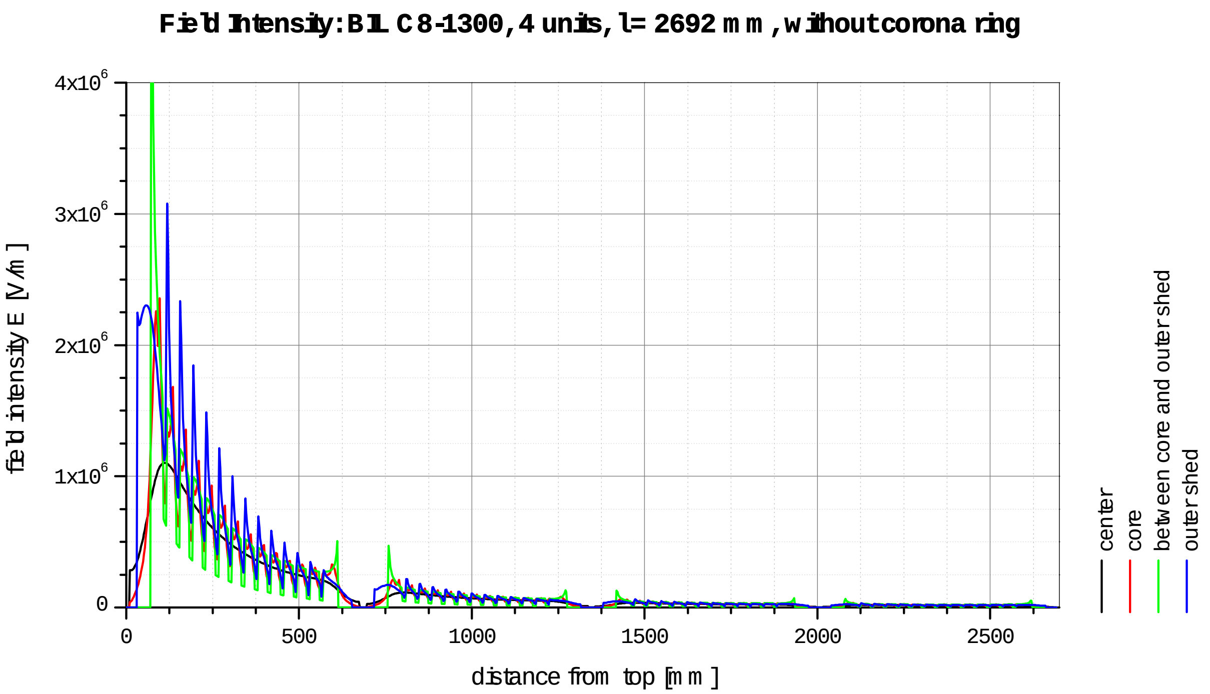


a) Voltage Characteristic along the whole insulator at different radial points

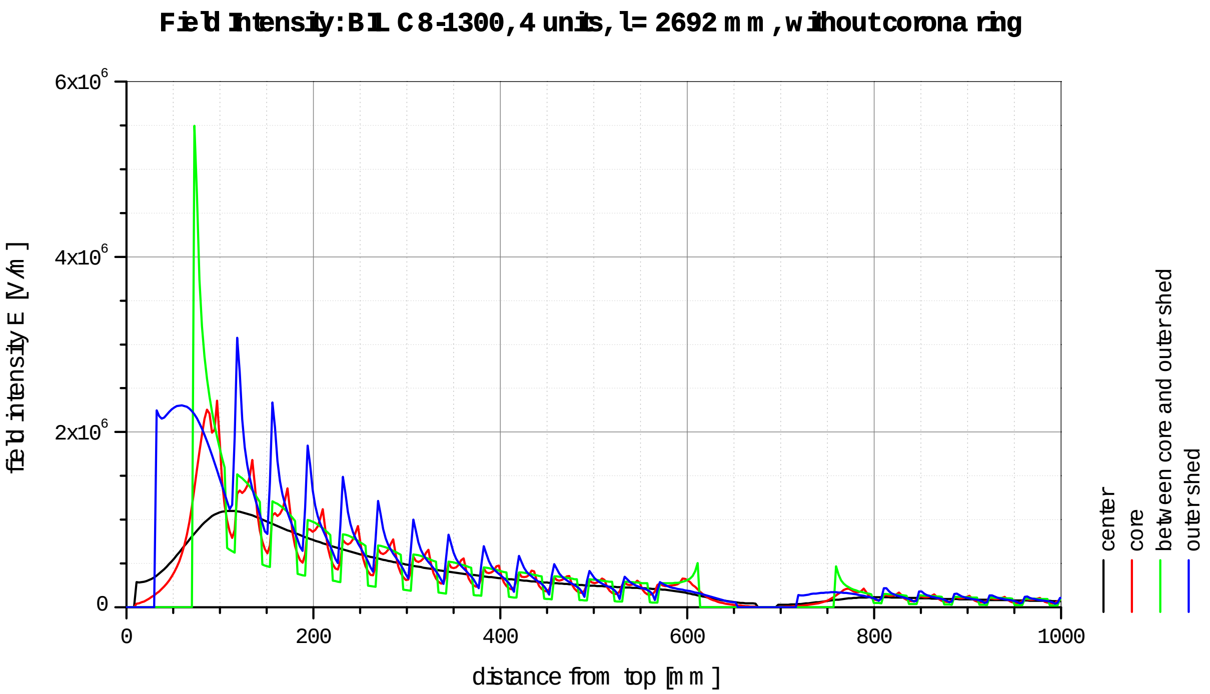


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 45: Voltage Characteristic: BIL C8-1300, 3 units, l = 2900 mm, without CR

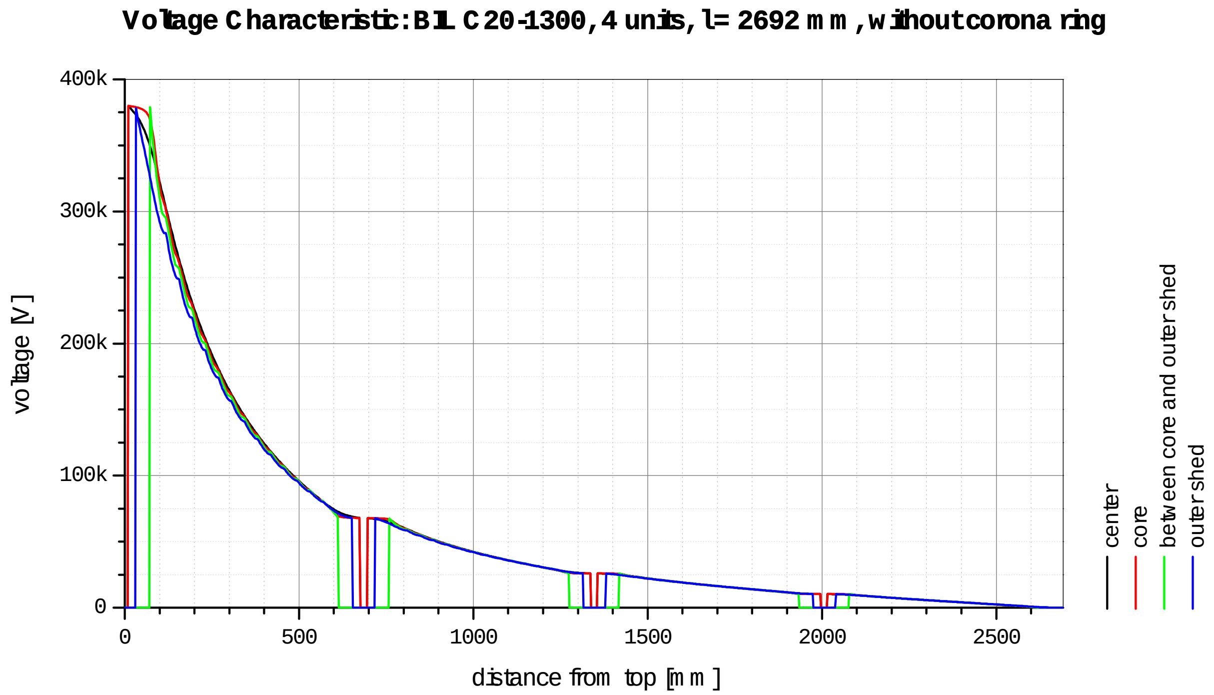


a) Course of the electric field along the whole insulator at different radial points

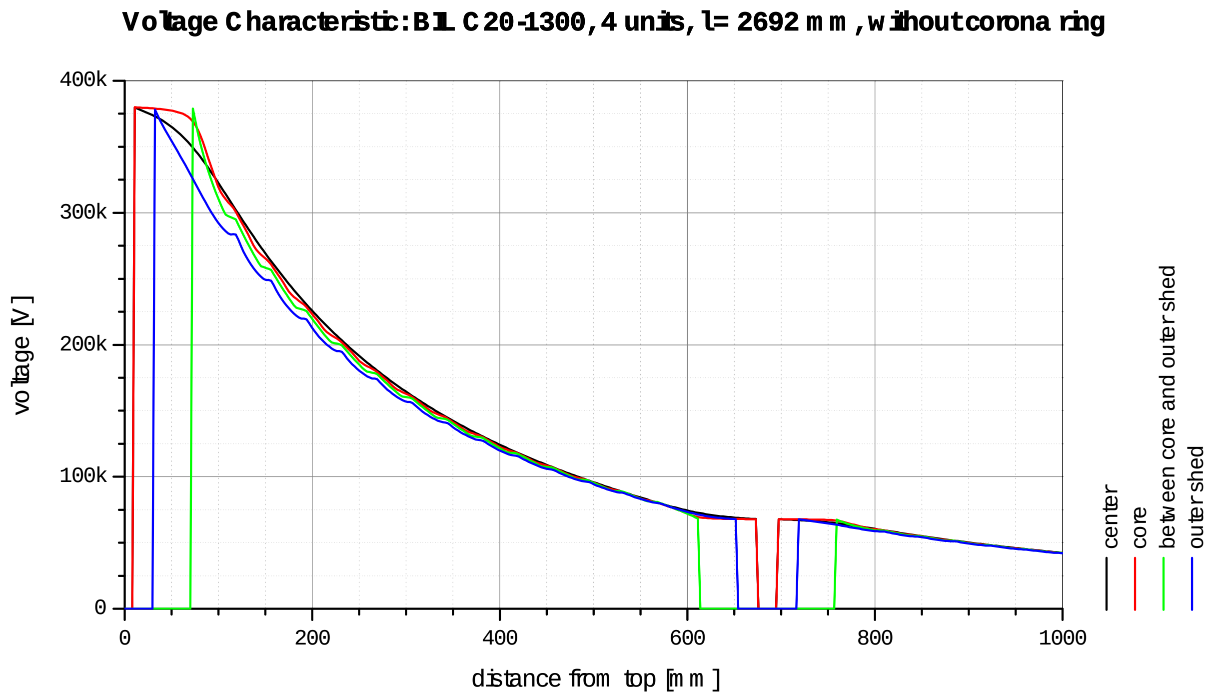


b) Course of the electric field along the first meter from the top at different radial points

Fig. 46: Field Intensity: BIL C8-1300, 4 units, l = 2692 mm, without CR



a) Voltage Characteristic along the whole insulator at different radial points

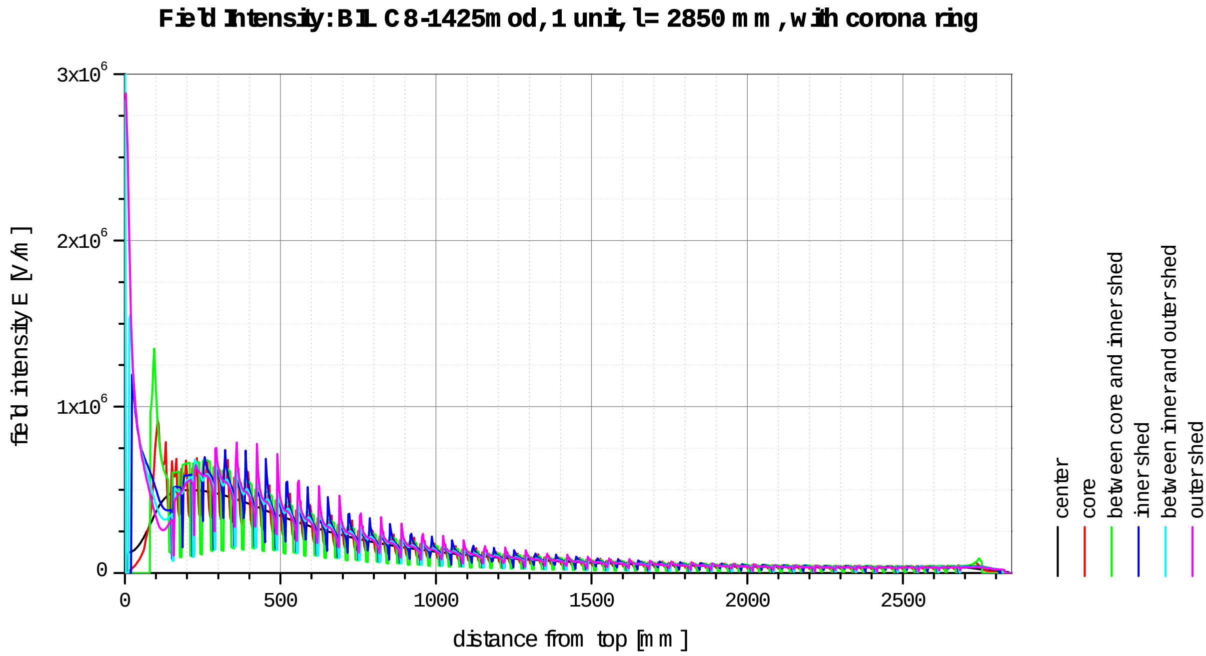


b) Voltage Characteristic along the first meter from the top at different radial points

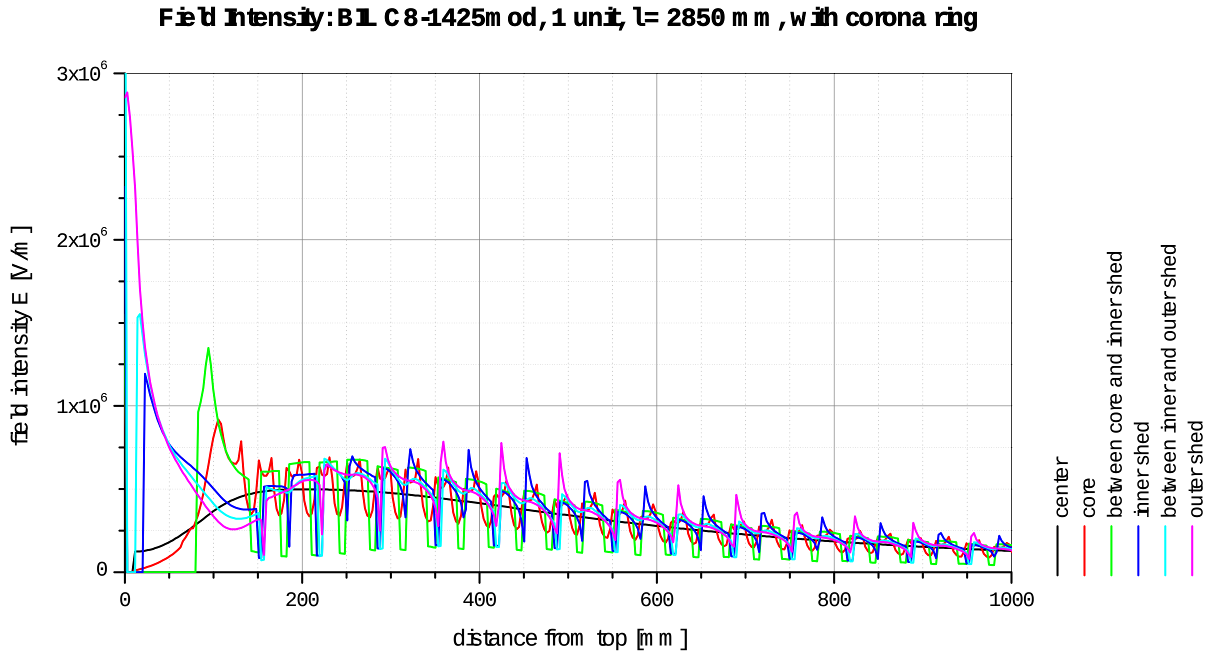
Fig. 47: Voltage Characteristic: BIL C8-1300, 4 units, l = 2692 *mm*, without CR

A.4 Electrostatic Field Simualtions for BIL 1425 insulators

In the following section the results of the electrostatic field simulations for insulator arrangements with a dry lightning impulse withstand voltage of 1425 kV can be found. All arrangements have been simulated at a system voltage of 400 kV. The graphs show the progression of the field intensity and voltage characteristic of the single insulator arrangement at different radial lines across the whole insulator.

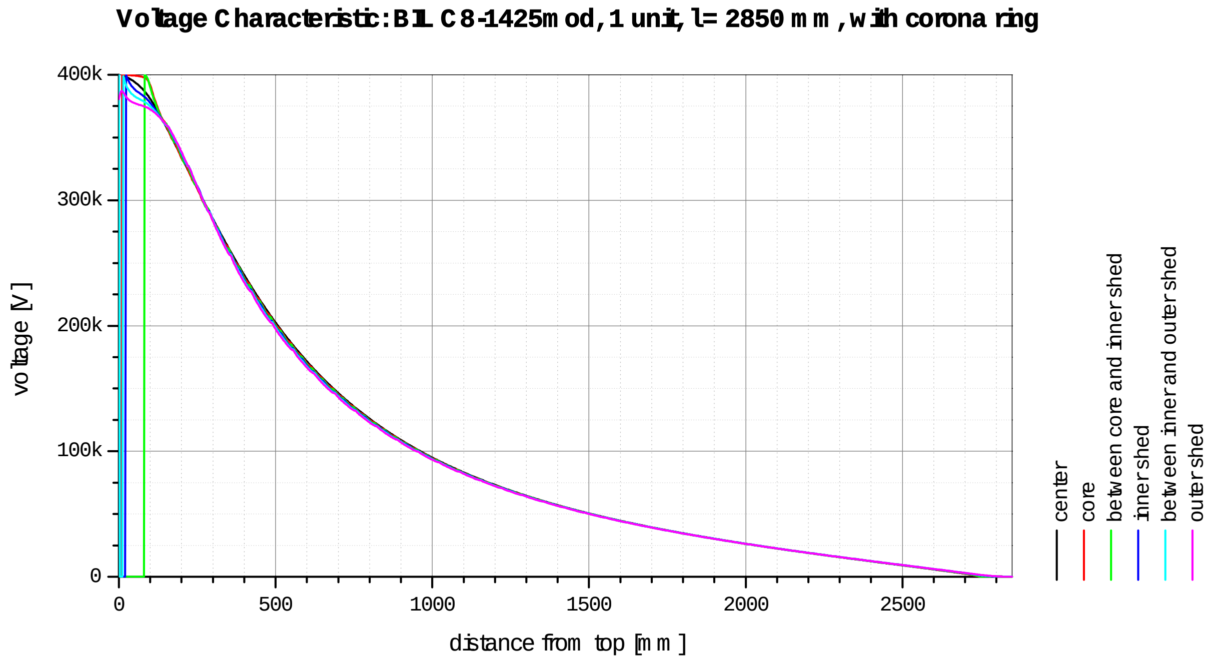


a) Course of the electric field along the whole insulator at different radial points

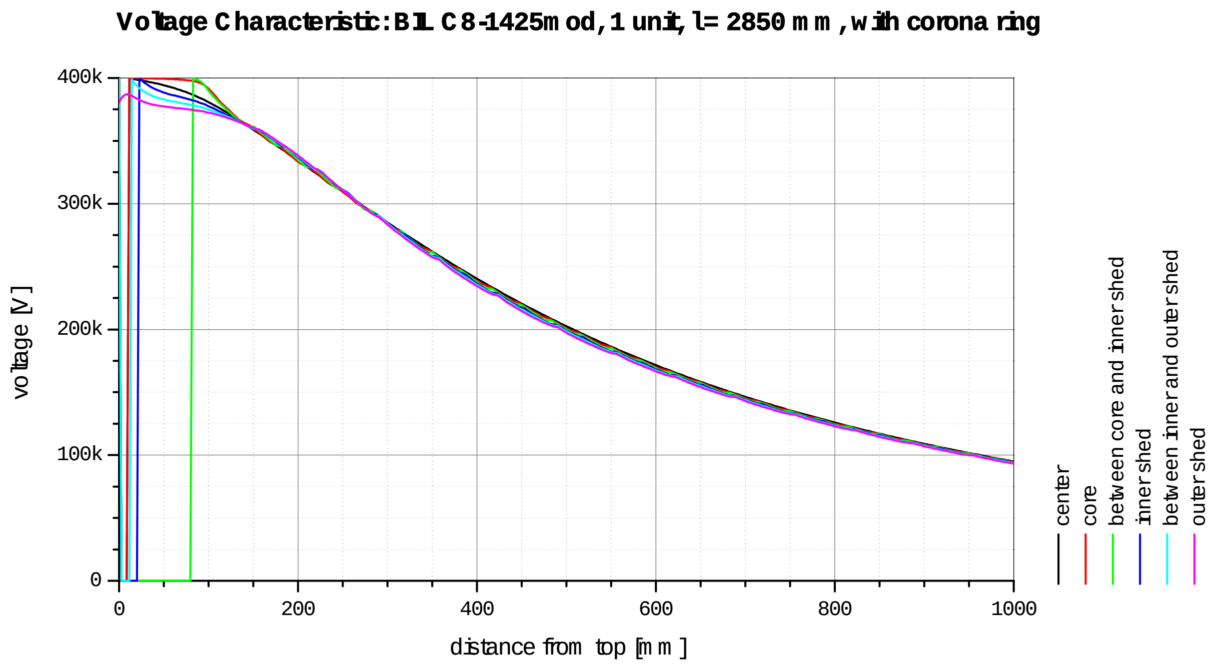


b) Course of the electric field along the first meter from the top at different radial points

Fig. 48: Field Intensity: BIL C8-1425mod, 1 unit, l = 2850 mm, with CR

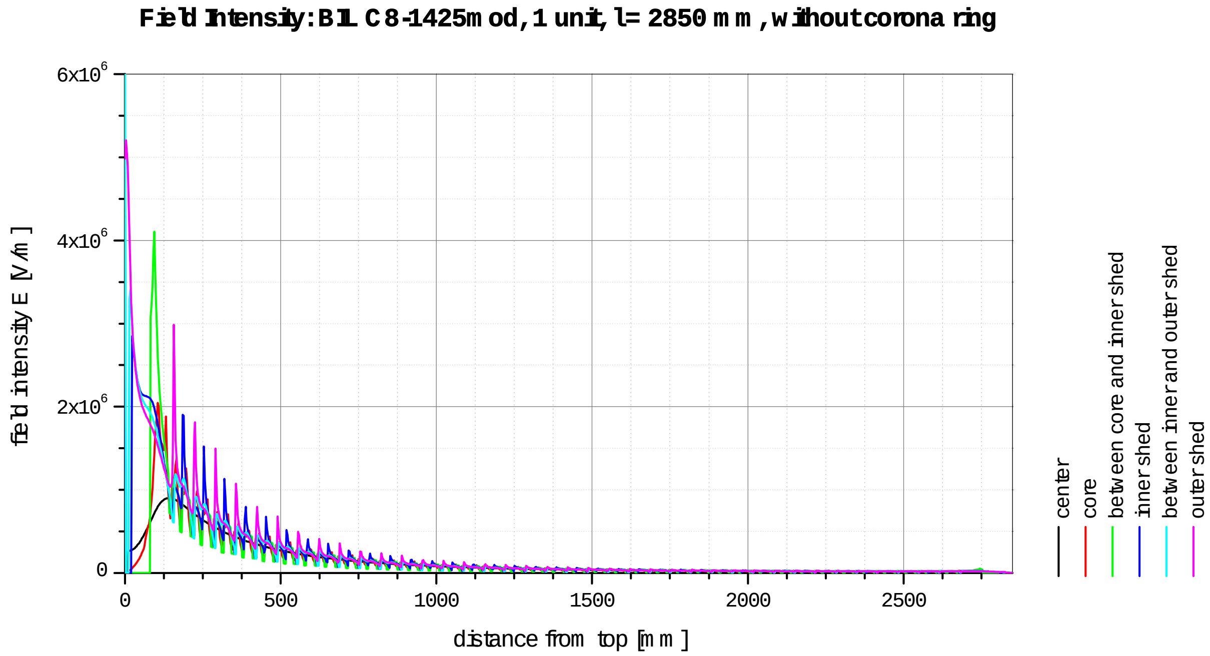


a) Voltage Characteristic along the whole insulator at different radial points

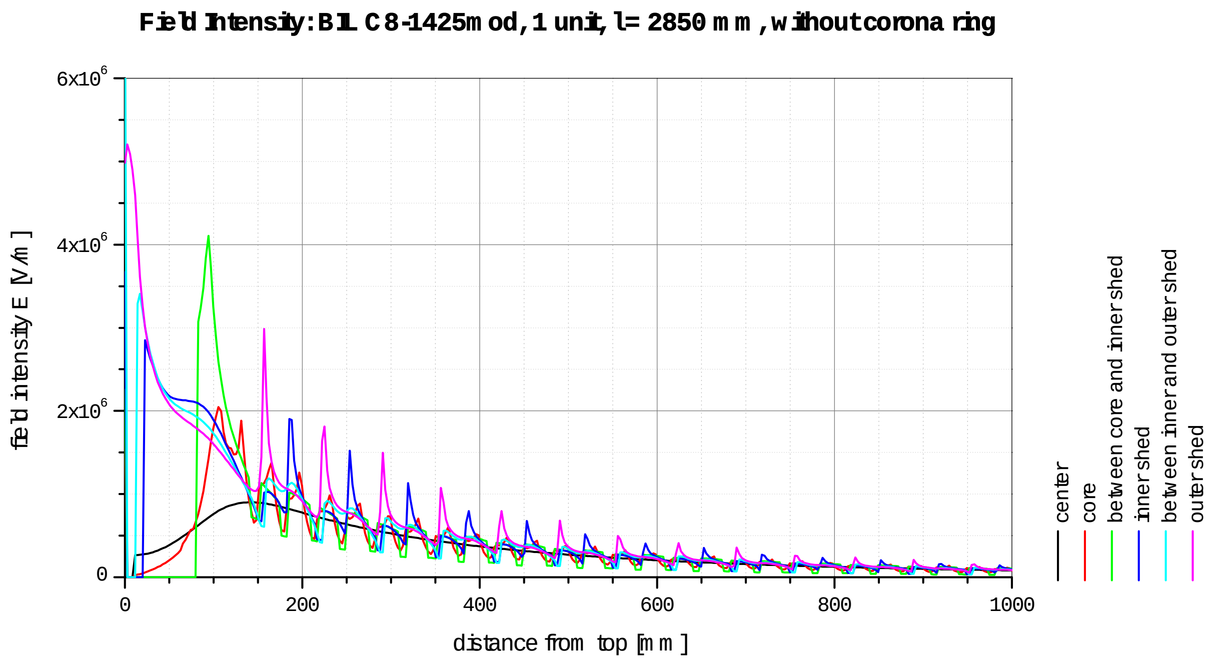


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 49: Voltage Characteristic: BIL C8-1425mod, 1 unit, l = 2850 mm, with CR

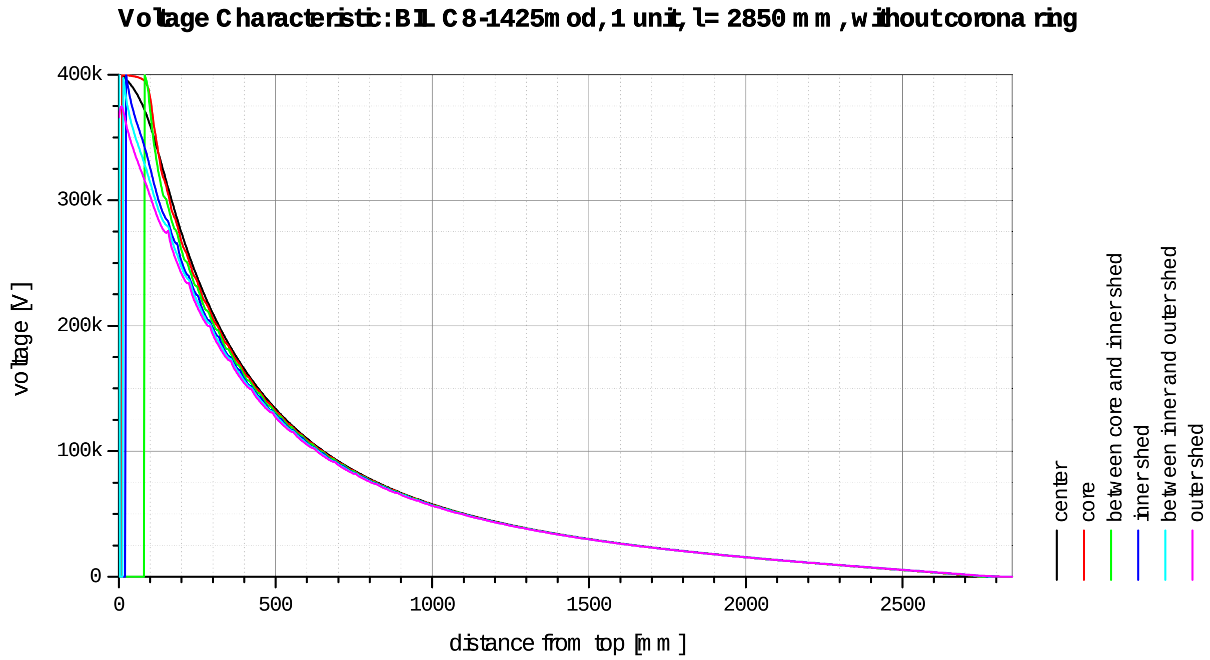


a) Course of the electric field along the whole insulator at different radial points

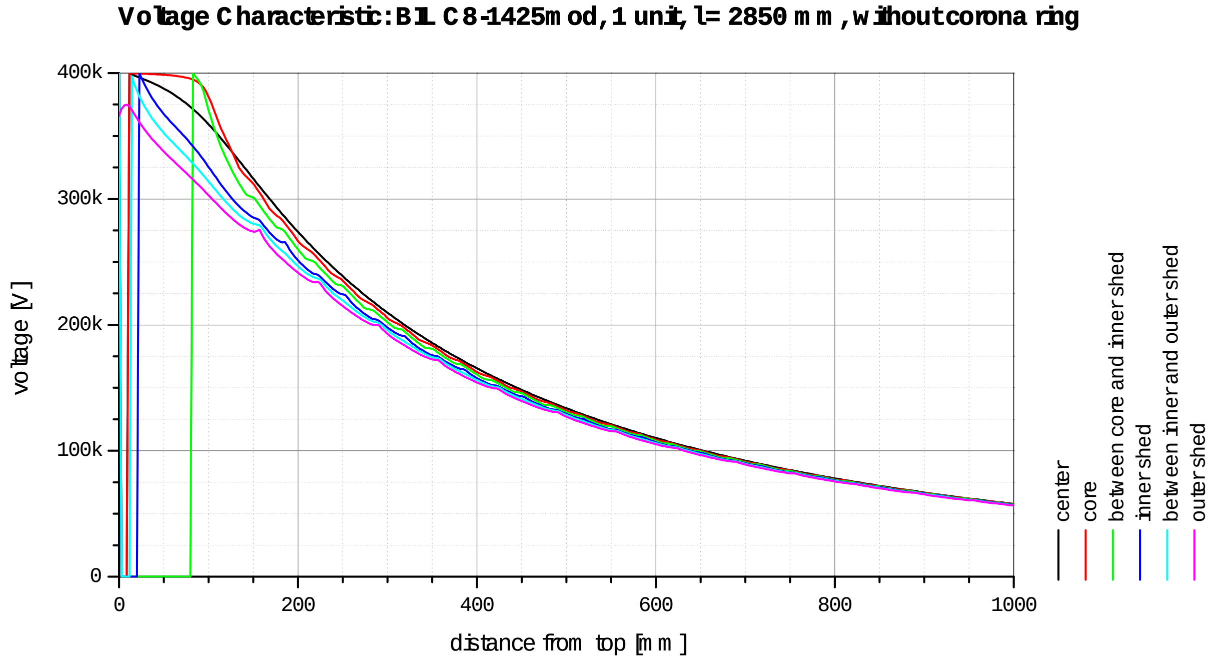


b) Course of the electric field along the first meter from the top at different radial points

Fig. 50: Field Intensity: BIL C8-1425mod, 1 unit, l = 2850 mm, without CR

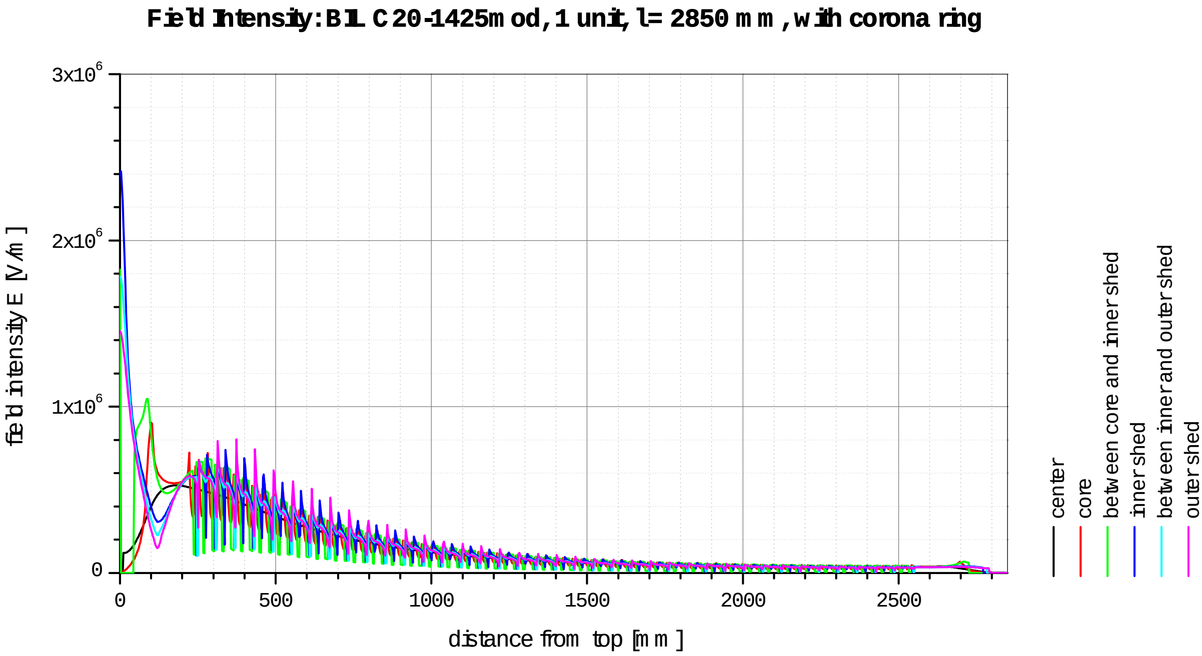


a) Voltage Characteristic along the whole insulator at different radial points

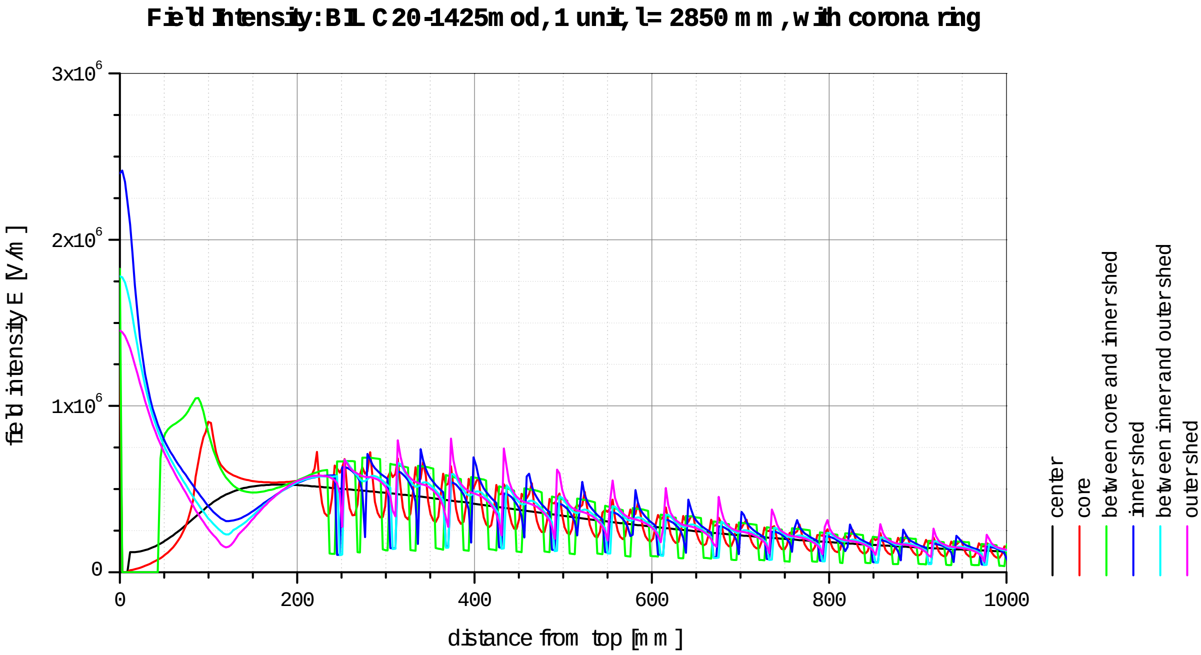


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 51: Voltage Characteristic: BIL C8-1425mod, 1 unit, l = 2850 mm, without CR

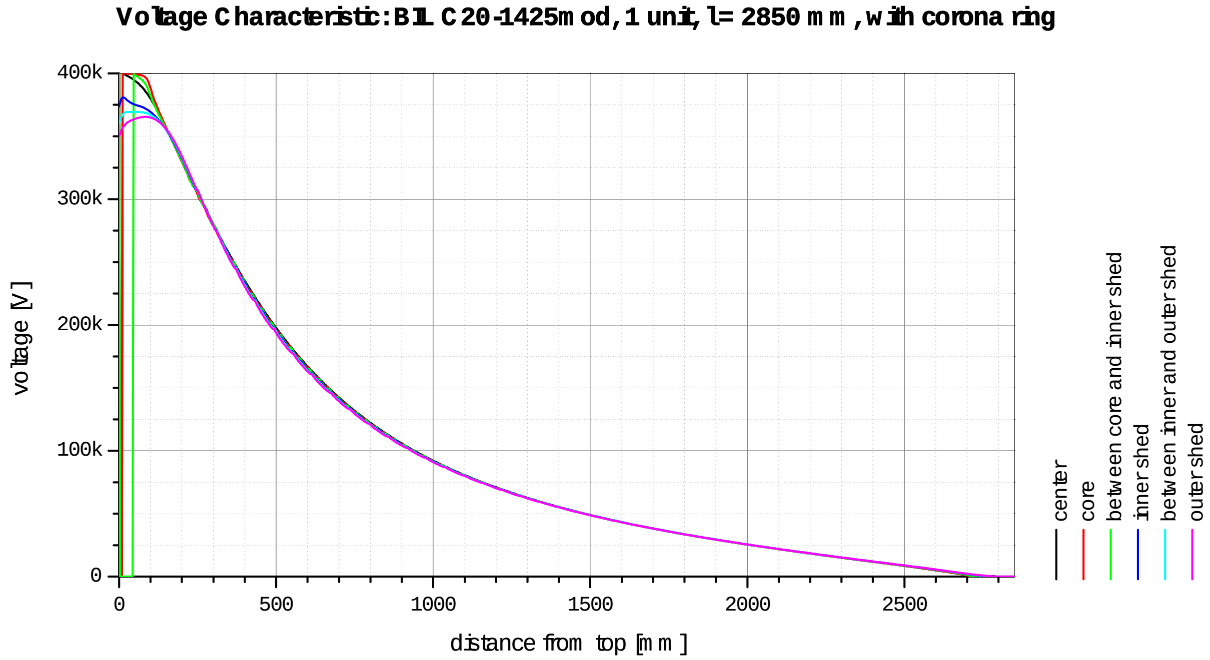


a) Course of the electric field along the whole insulator at different radial points

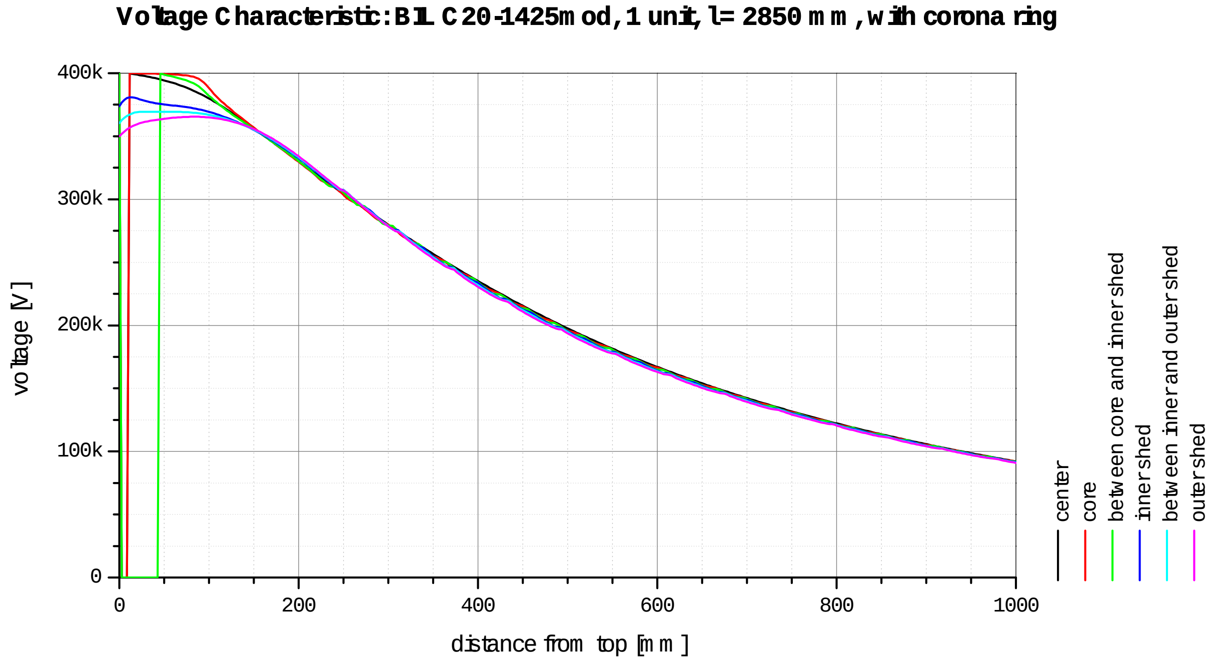


b) Course of the electric field along the first meter from the top at different radial points

Fig. 52: Field Intensity: BIL C20-1425mod, 1 unit, l = 2850 mm, with CR

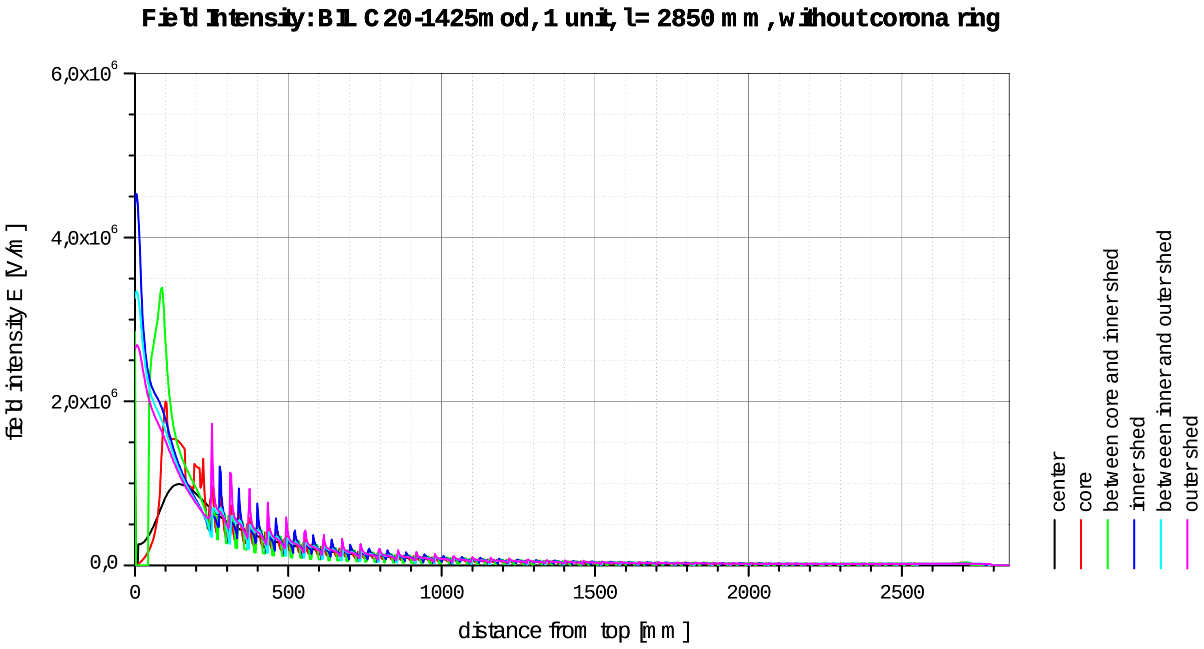


a) Voltage Characteristic along the whole insulator at different radial points

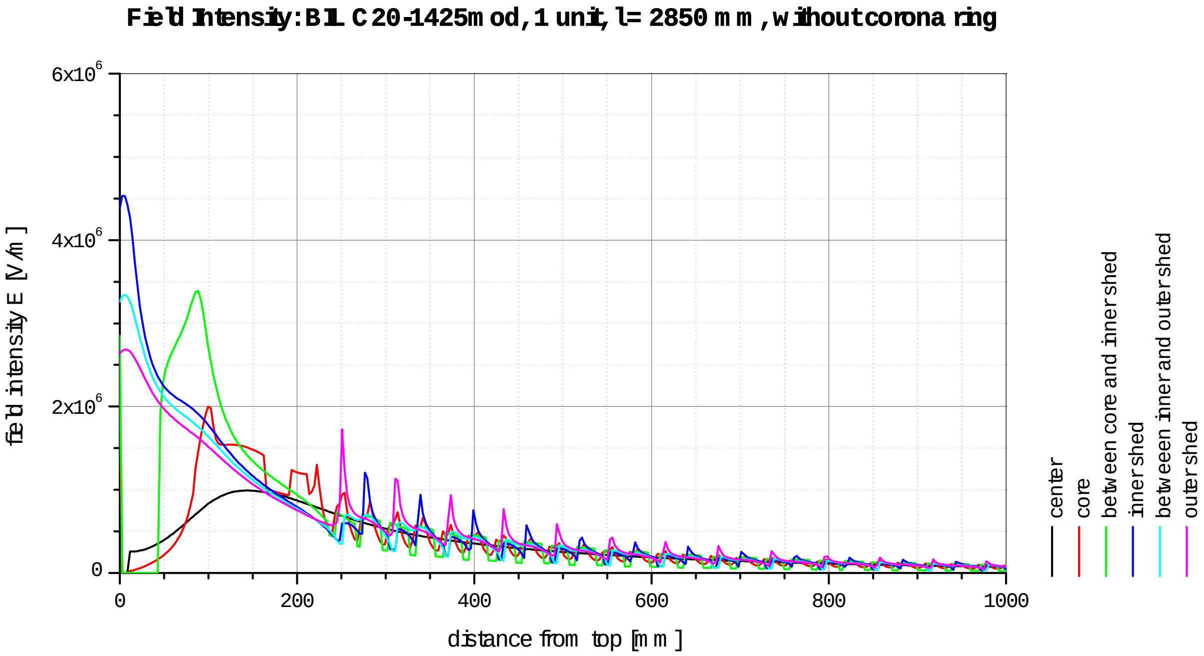


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 53: Voltage Characteristic: BIL C20-1425mod, 1 unit, l = 2850 mm, with CR

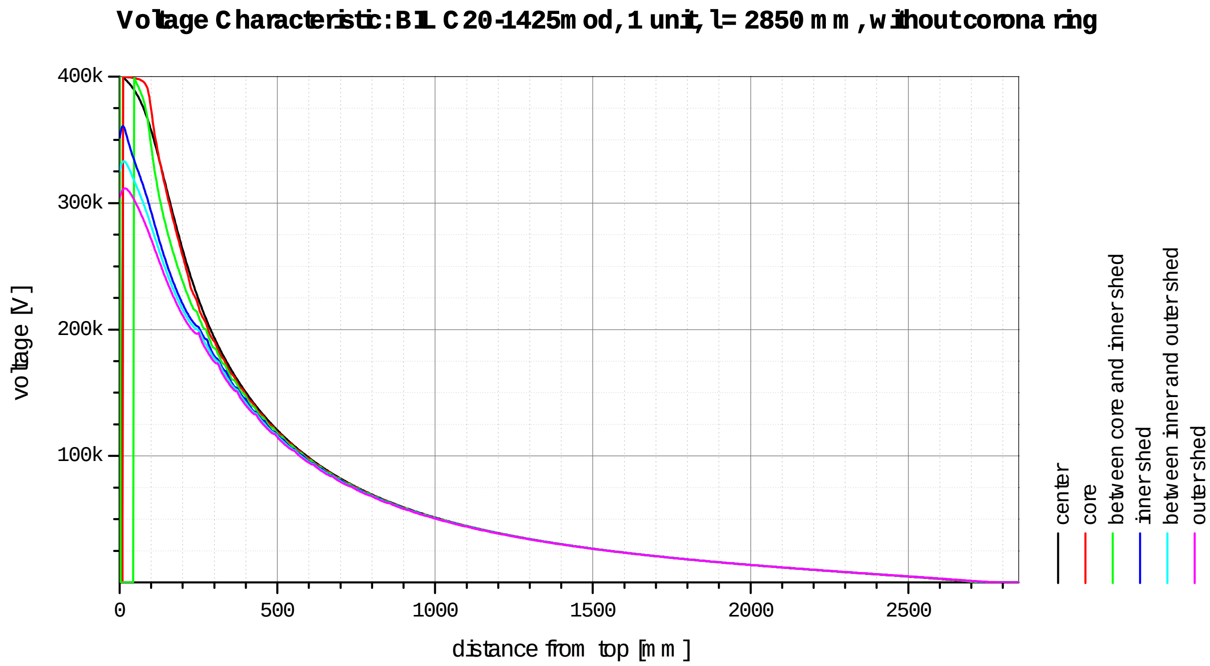


a) Course of the electric field along the whole insulator at different radial points

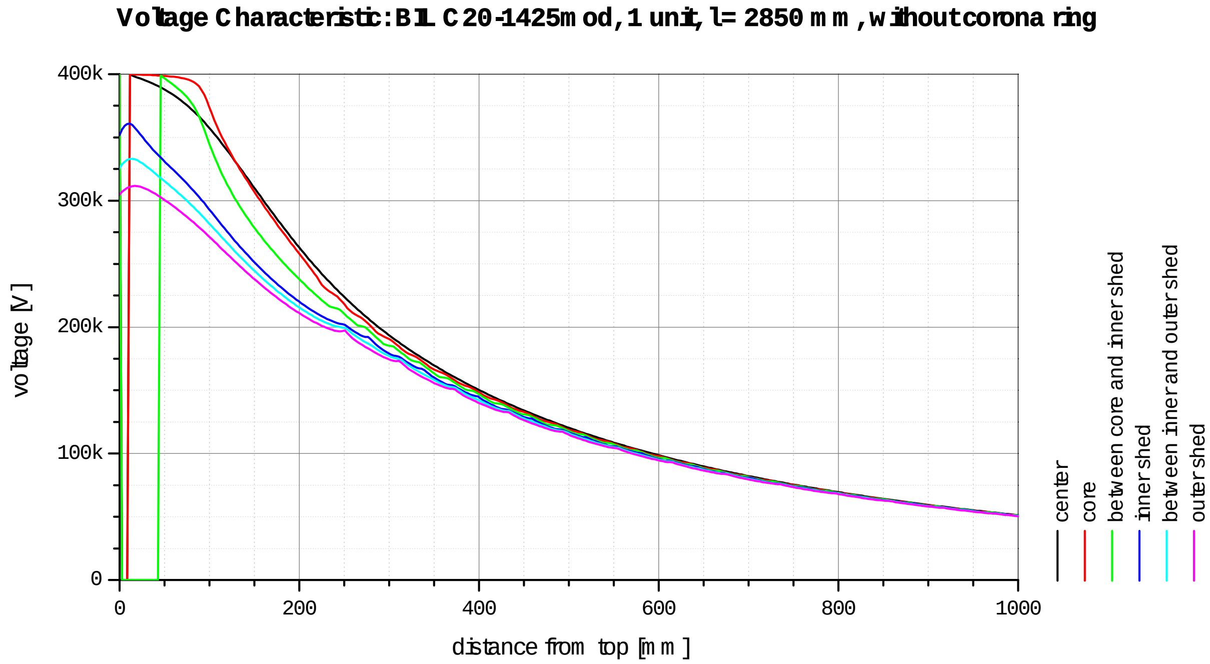


b) Course of the electric field along the first meter from the top at different radial points

Fig. 54: Field Intensity: BIL C20-1425mod, 1 unit, l = 2850 *mm*, without CR

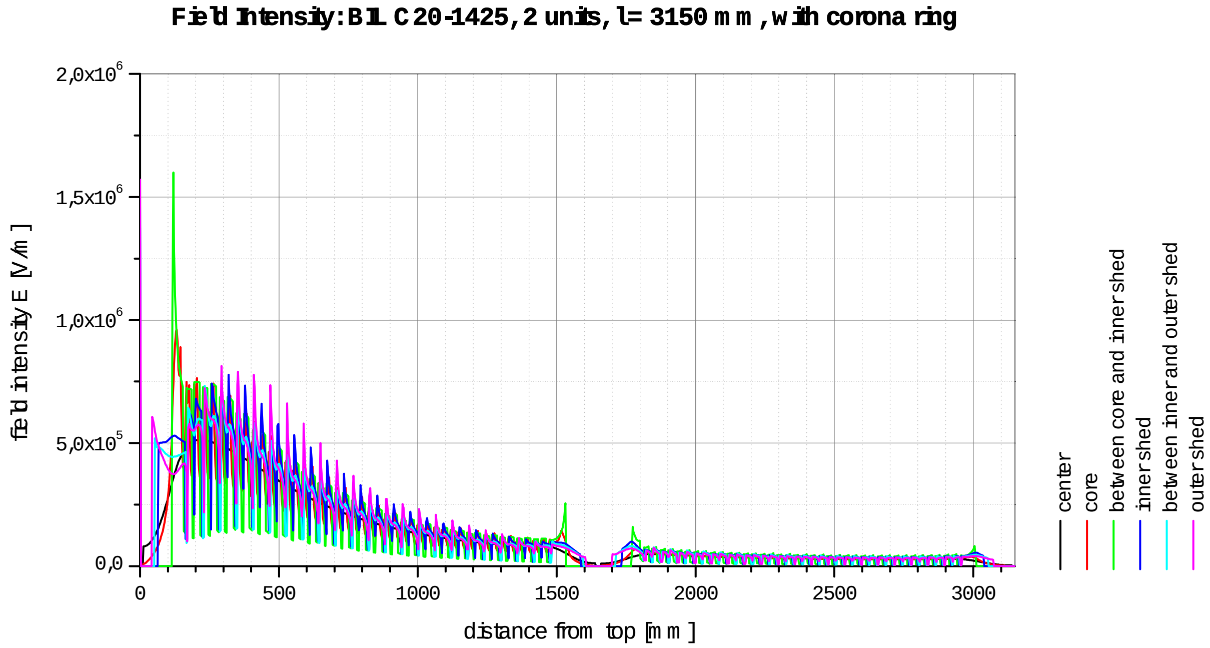


a) Voltage Characteristic along the whole insulator at different radial points

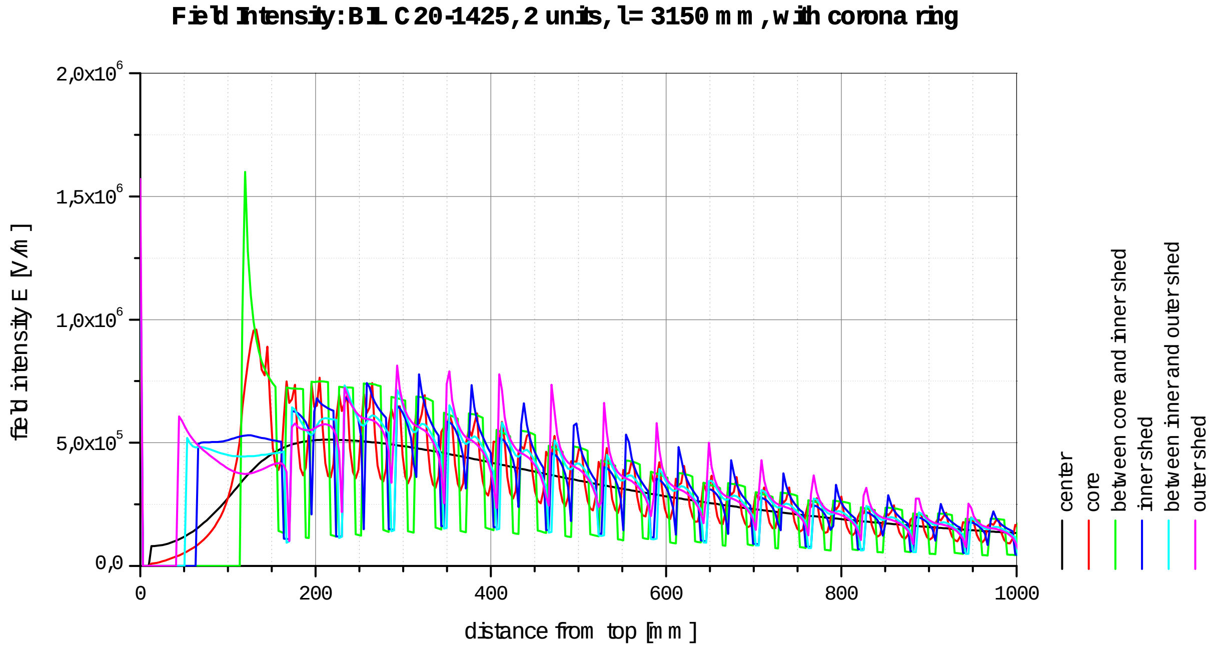


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 55: Voltage Characteristic: BIL C20-1425mod, 1 unit, l = 2850 mm, without CR

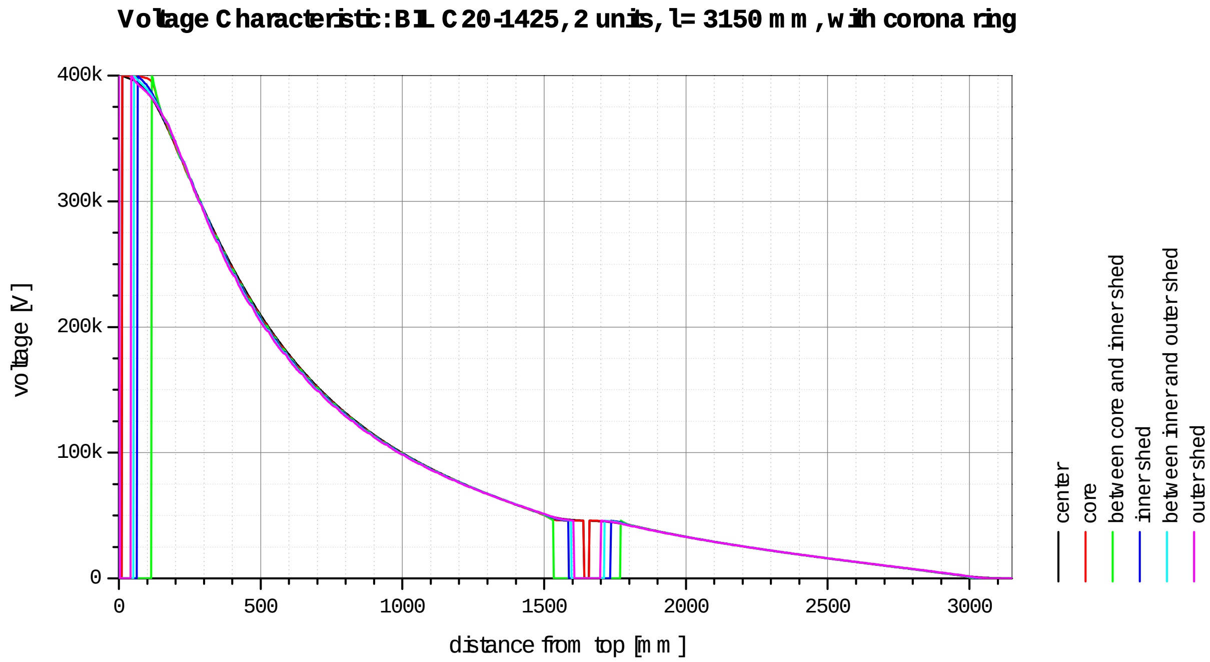


a) Course of the electric field along the whole insulator at different radial points

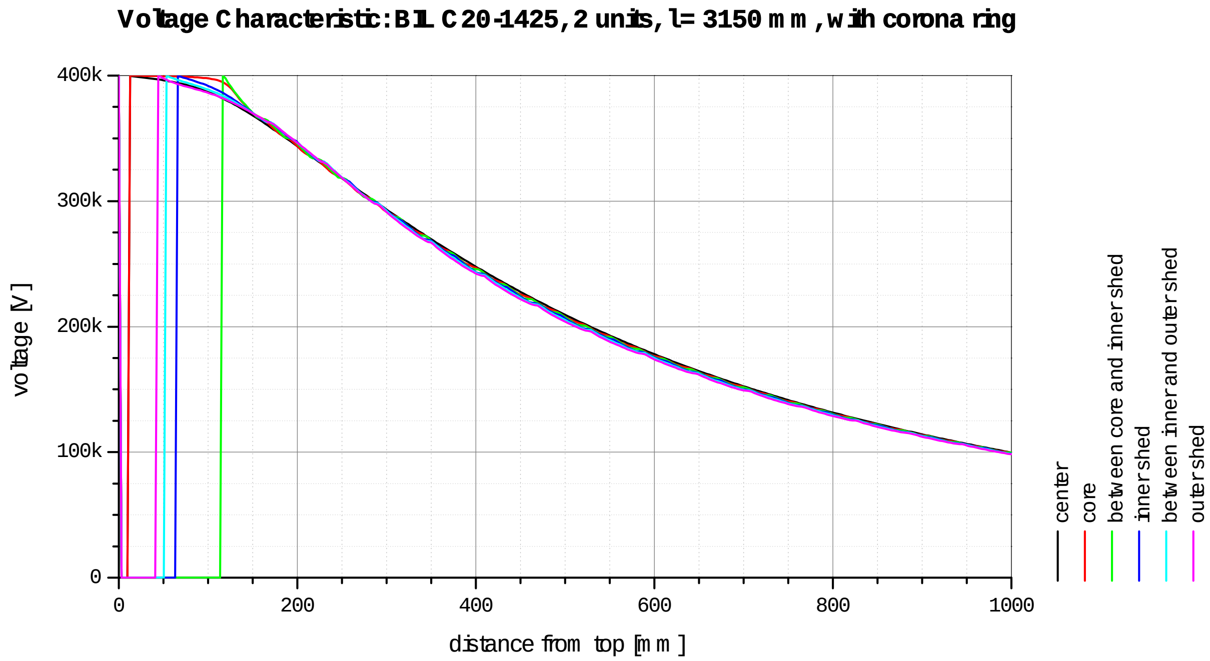


b) Course of the electric field along the first meter from the top at different radial points

Fig. 56: Field Intensity: BIL C20-1425, 2 units, l = 3150 mm, with CR

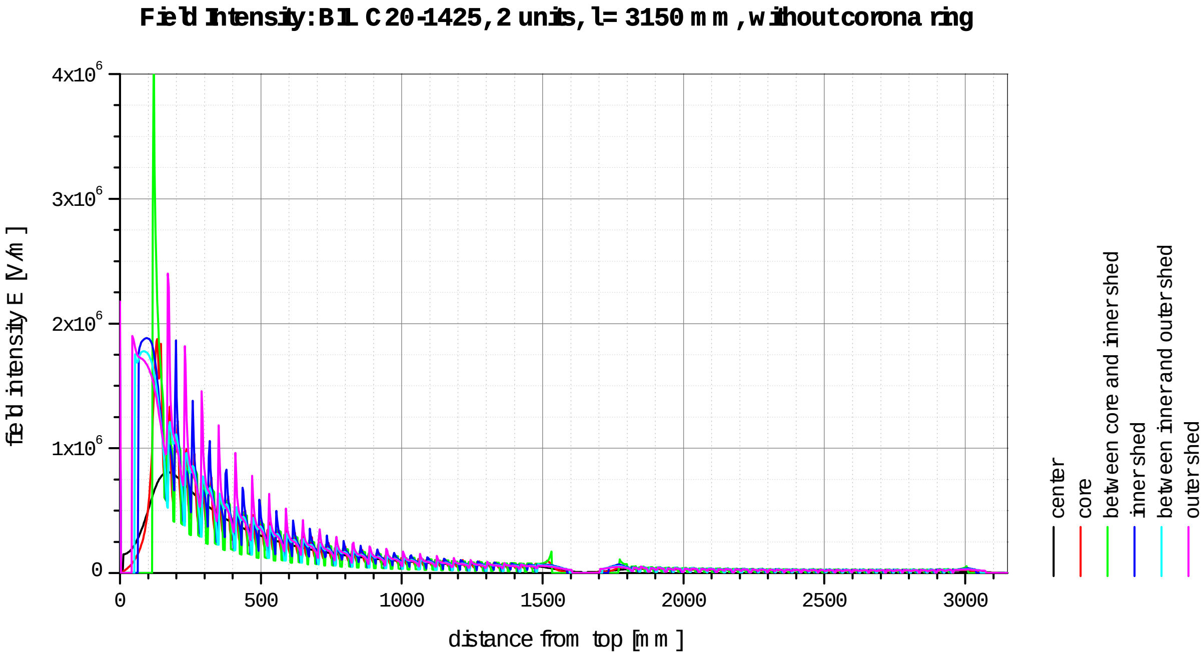


a) Voltage Characteristic along the whole insulator at different radial points

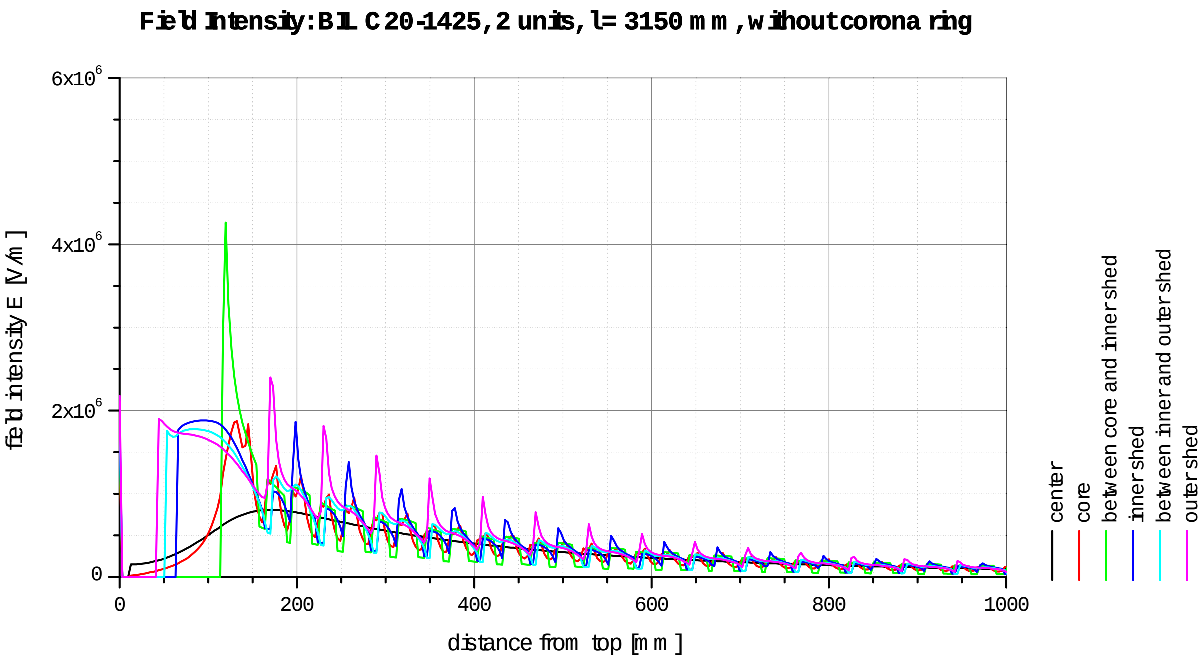


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 57: Voltage Characteristic: BIL C20-1425, 2 units, l = 3150 mm, with CR

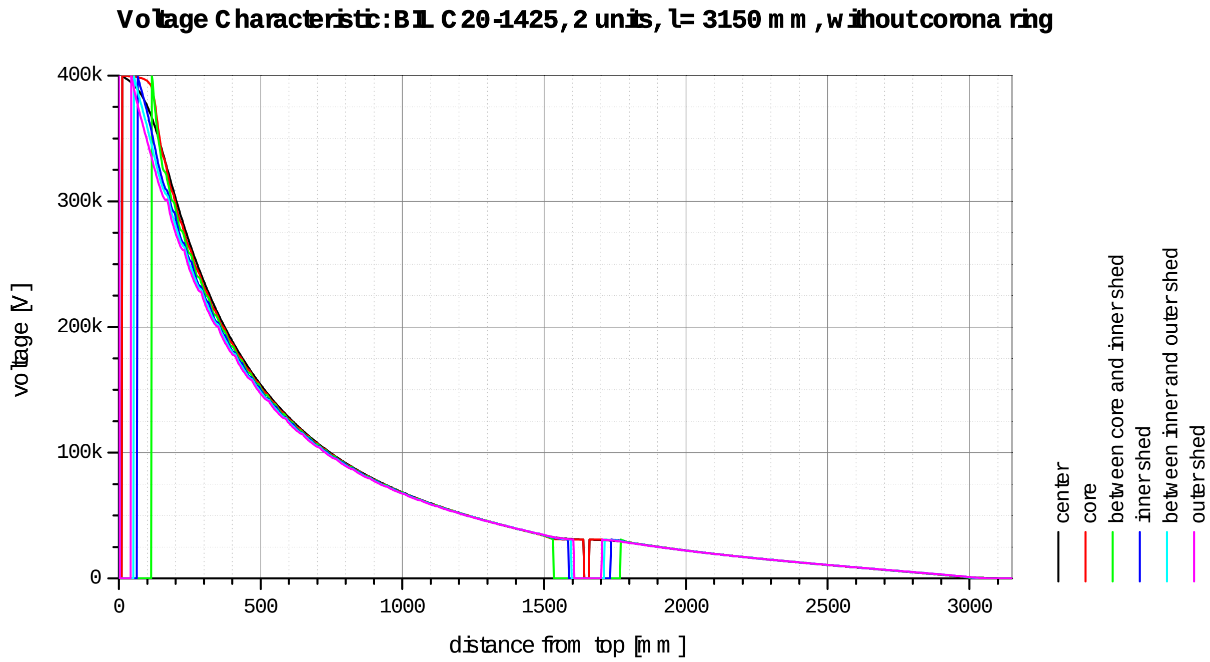


a) Course of the electric field along the whole insulator at different radial points

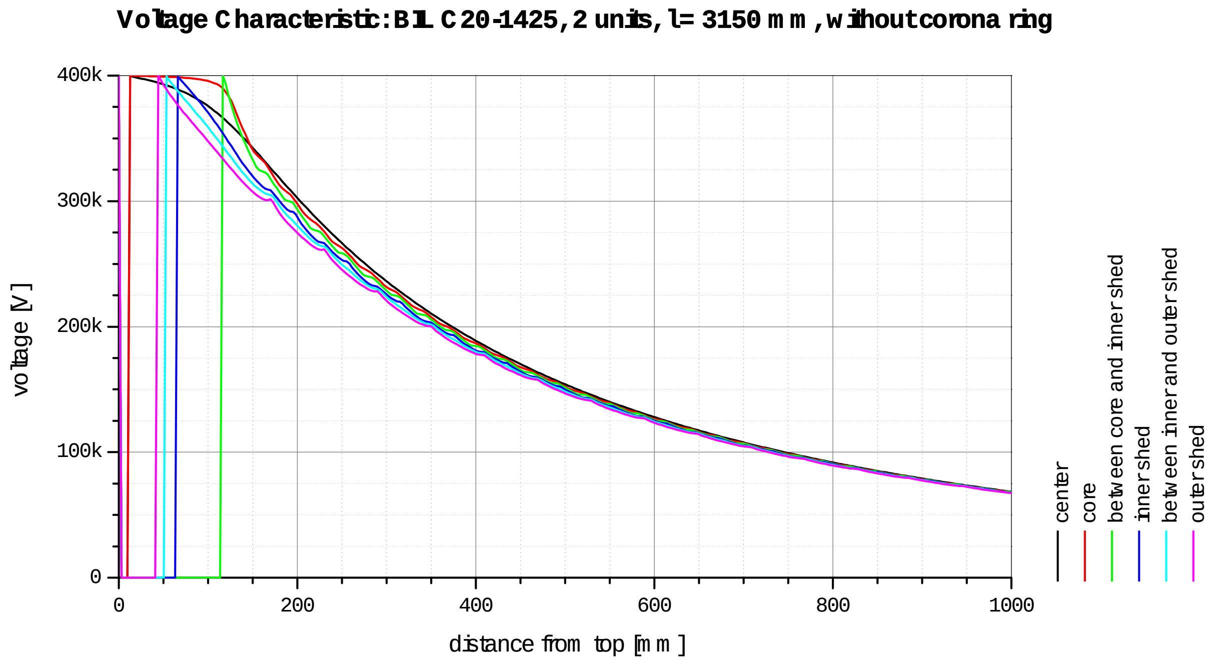


b) Course of the electric field along the first meter from the top at different radial points

Fig. 58: Field Intensity: BIL C20-1425, 2 units, l = 3150 mm, without CR

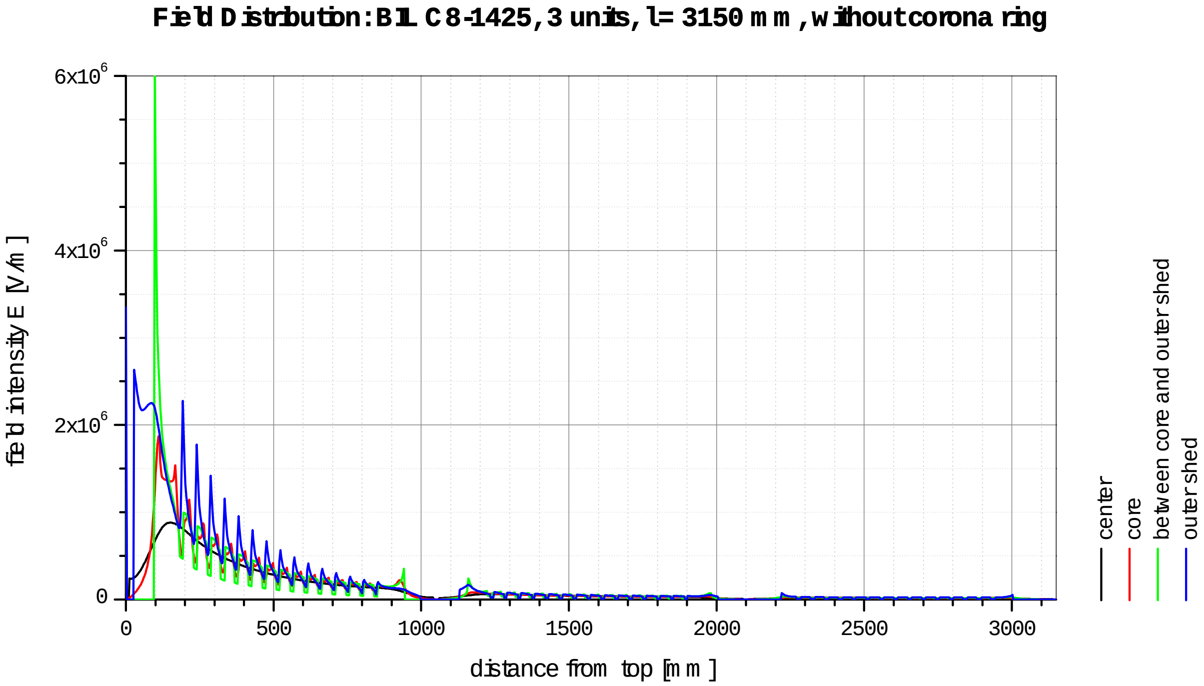


a) Voltage Characteristic along the whole insulator at different radial points

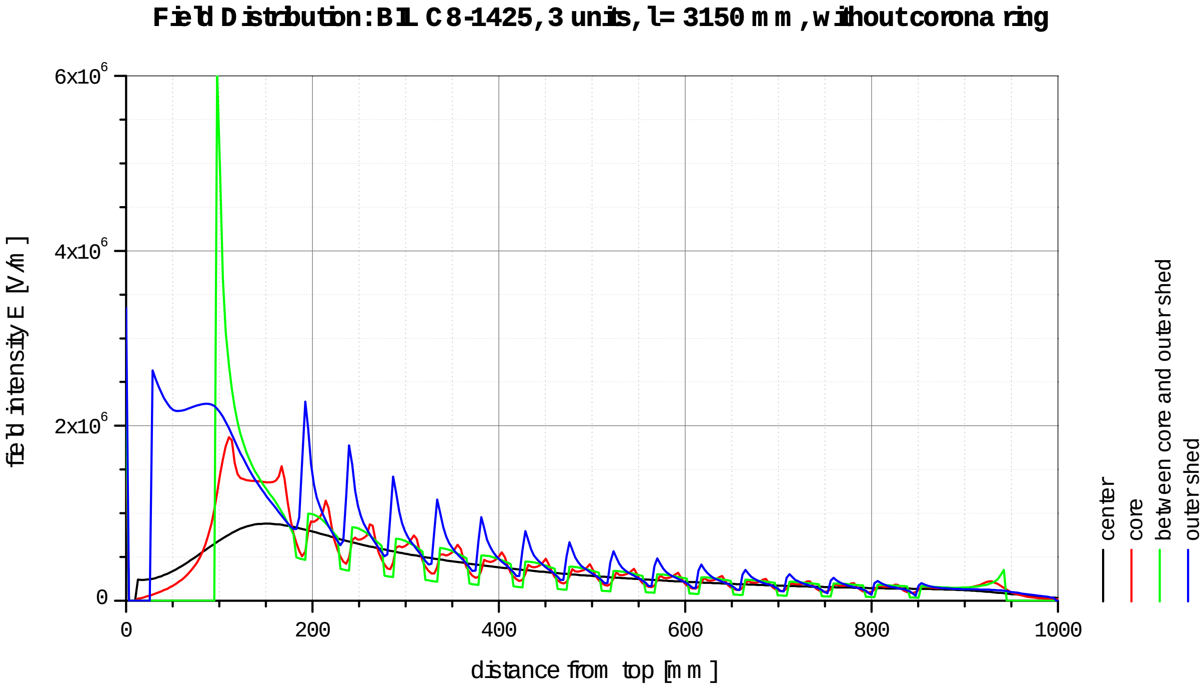


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 59: Voltage Characteristic: BIL C20-1425, 2 units, l = 3150 mm, without CR

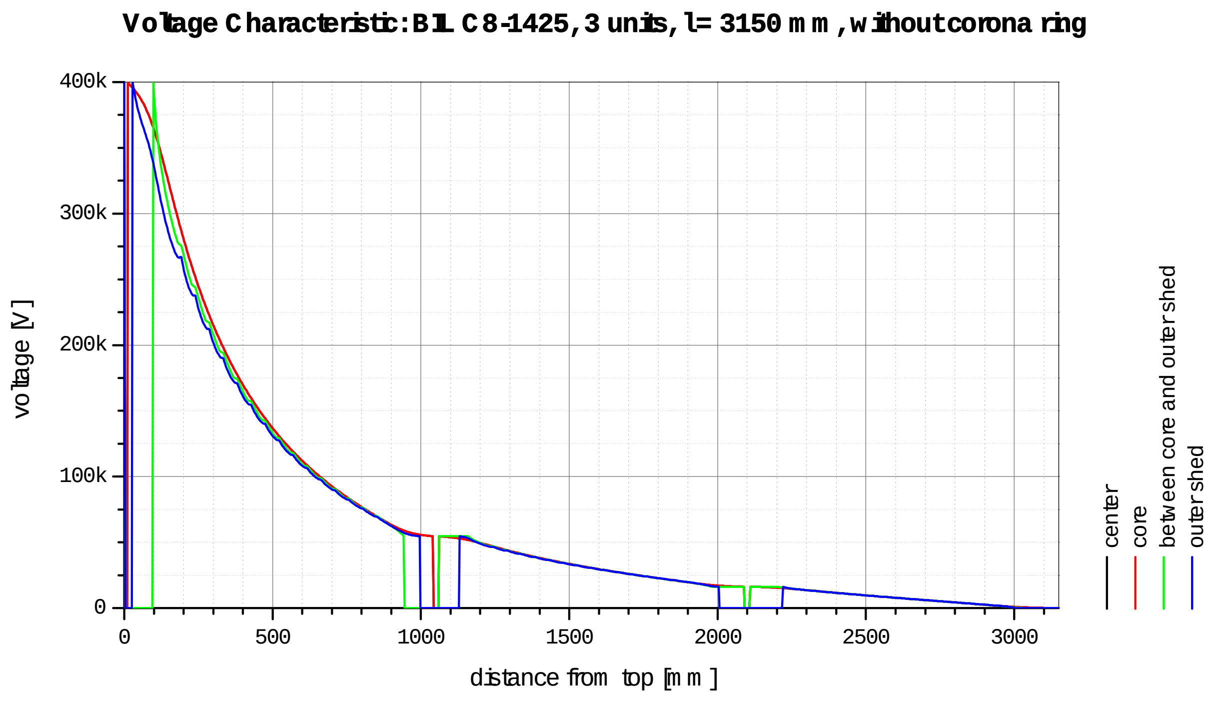


a) Course of the electric field along the whole insulator at different radial points

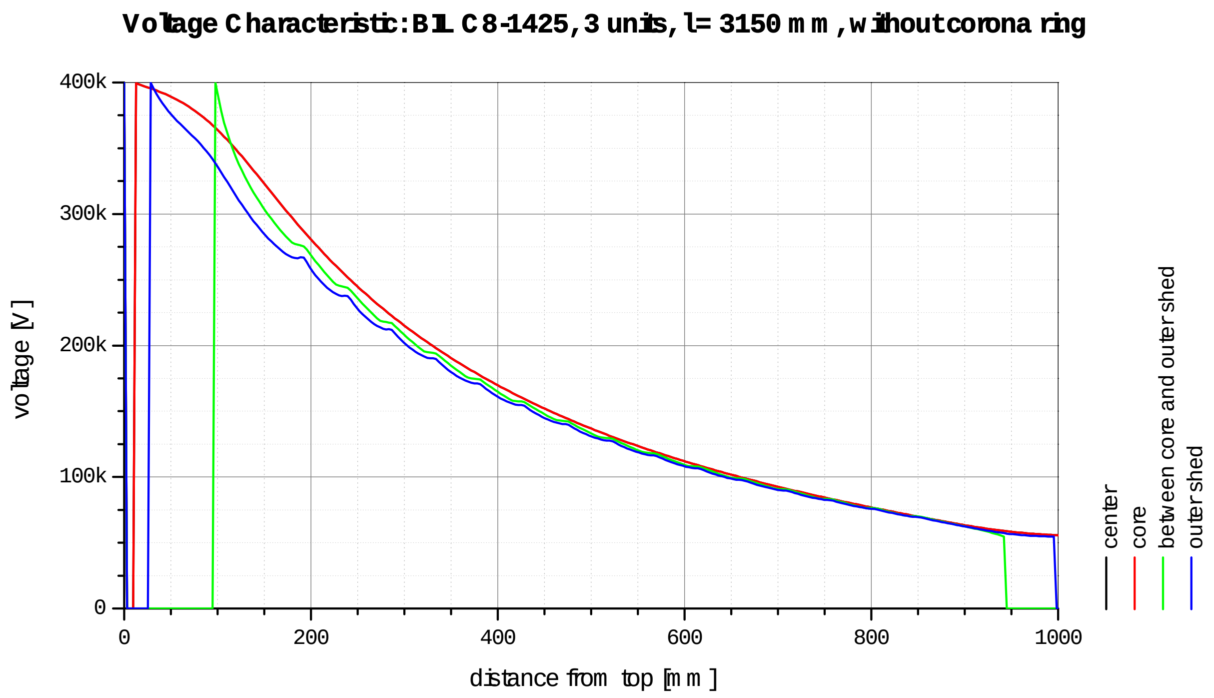


b) Course of the electric field along the first meter from the top at different radial points

Fig. 60: Field Distribution: BIL C8-1425, 3 units, l = 3150 mm, without CR



a) Voltage Characteristic along the whole insulator at different radial points

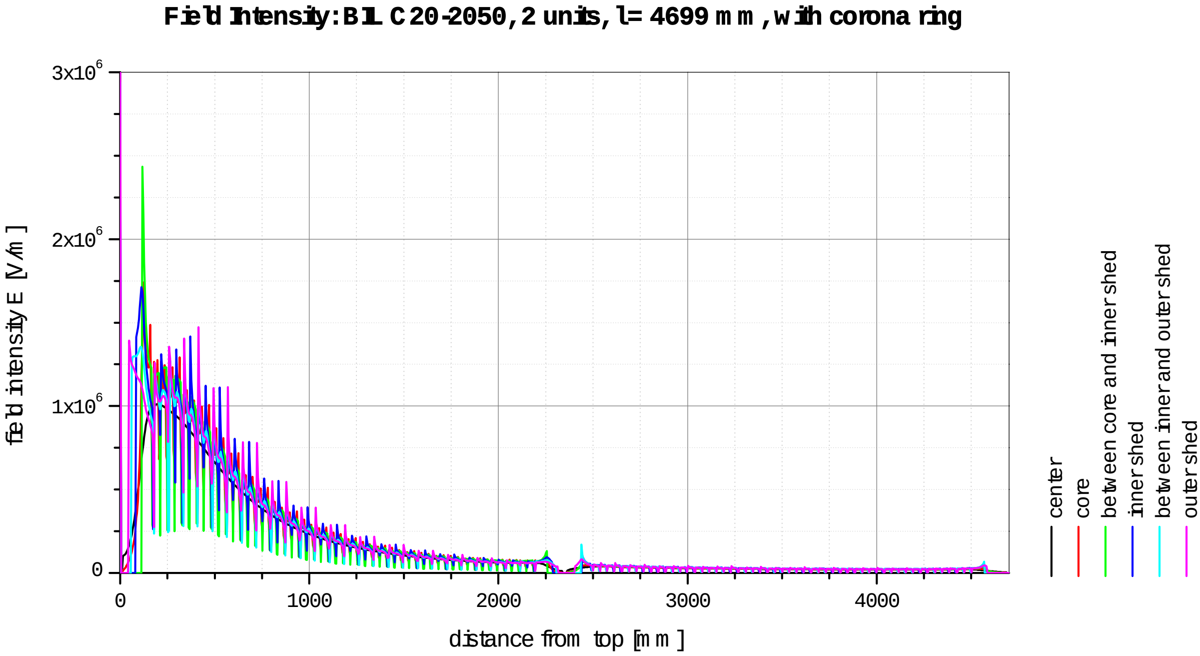


b) Voltage Characteristic along the first meter from the top at different radial points

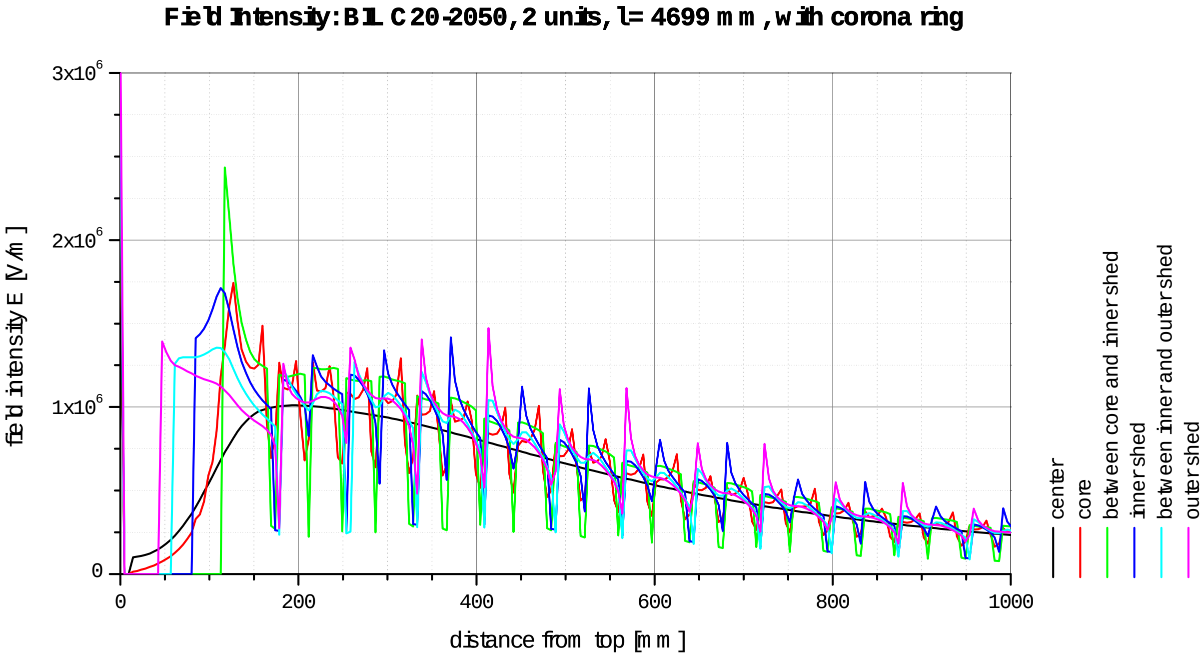
Fig. 61: Voltage Characteristic: BIL C8-1425, 3 units, l = 3150 mm, without CR

A.5 Electrostatic Field Simualtions for BIL 2050 insulators

In the following section the results of the electrostatic field simulations for insulator arrangements with a dry lightning impulse withstand voltage of 2050 kV can be found. All arrangements have been simulated at a system voltage of 765 kV. The graphs show the progression of the field intensity and voltage characteristic of the single insulator arrangement at different radial lines across the whole insulator.

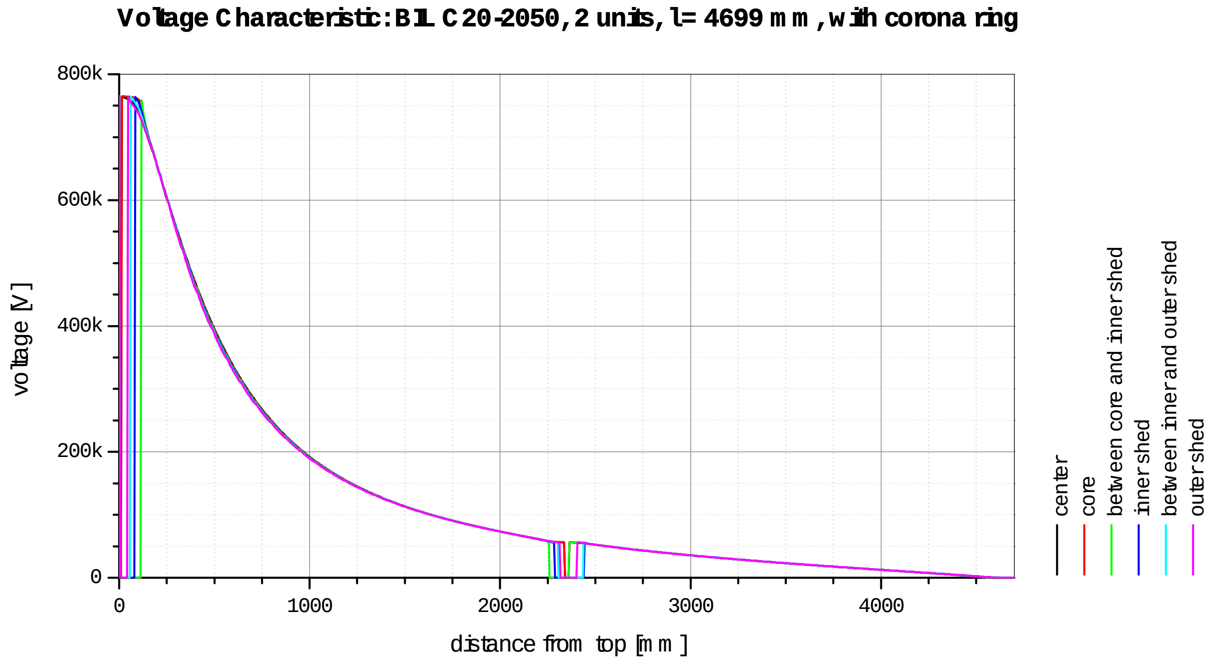


a) Course of the electric field along the whole insulator at different radial points

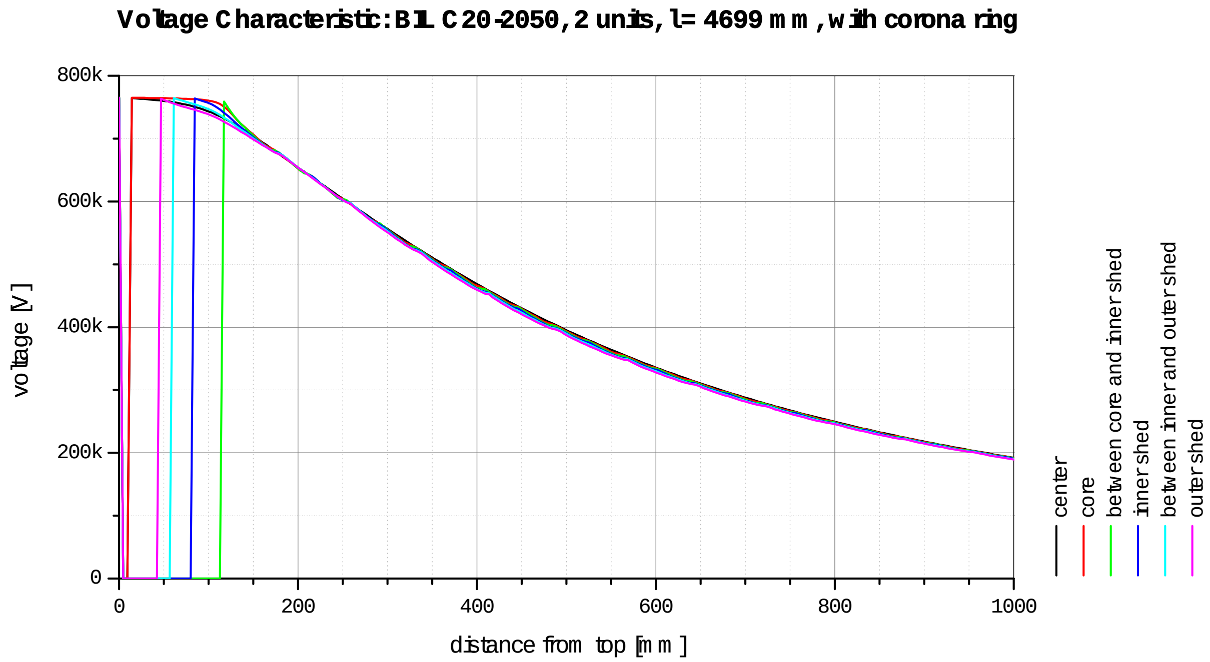


b) Course of the electric field along the first meter from the top at different radial points

Fig. 62: Field Distribution: BIL C20-2050, 2 units, l = 4699 mm, with CR

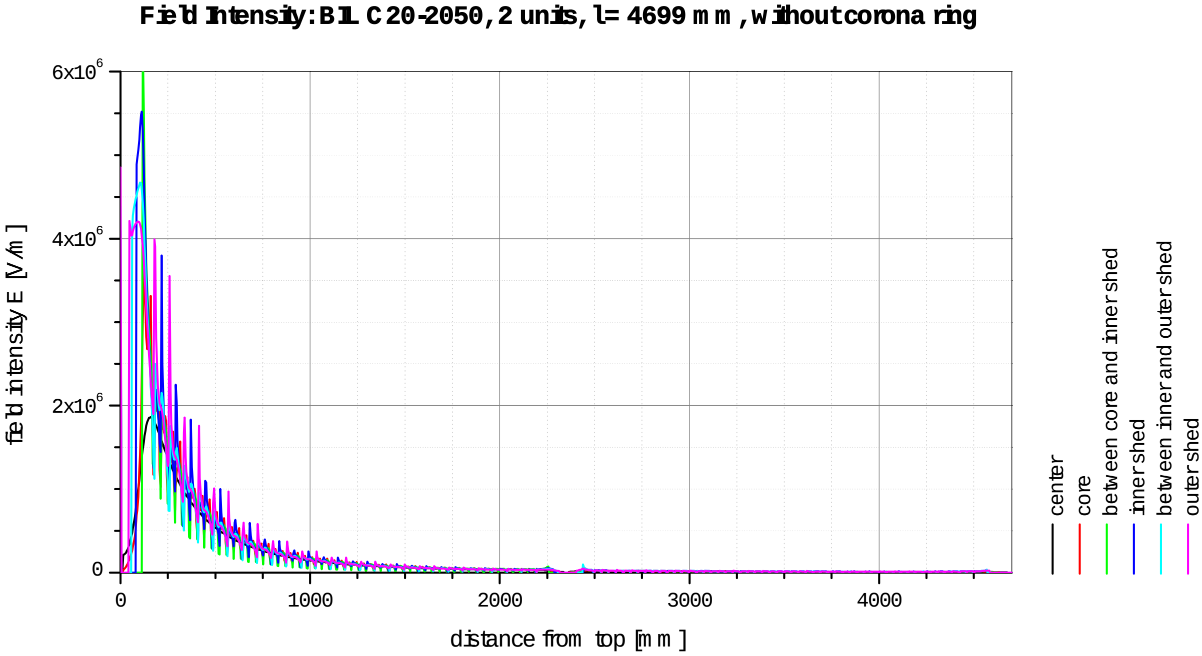


a) Voltage Characteristic along the whole insulator at different radial points

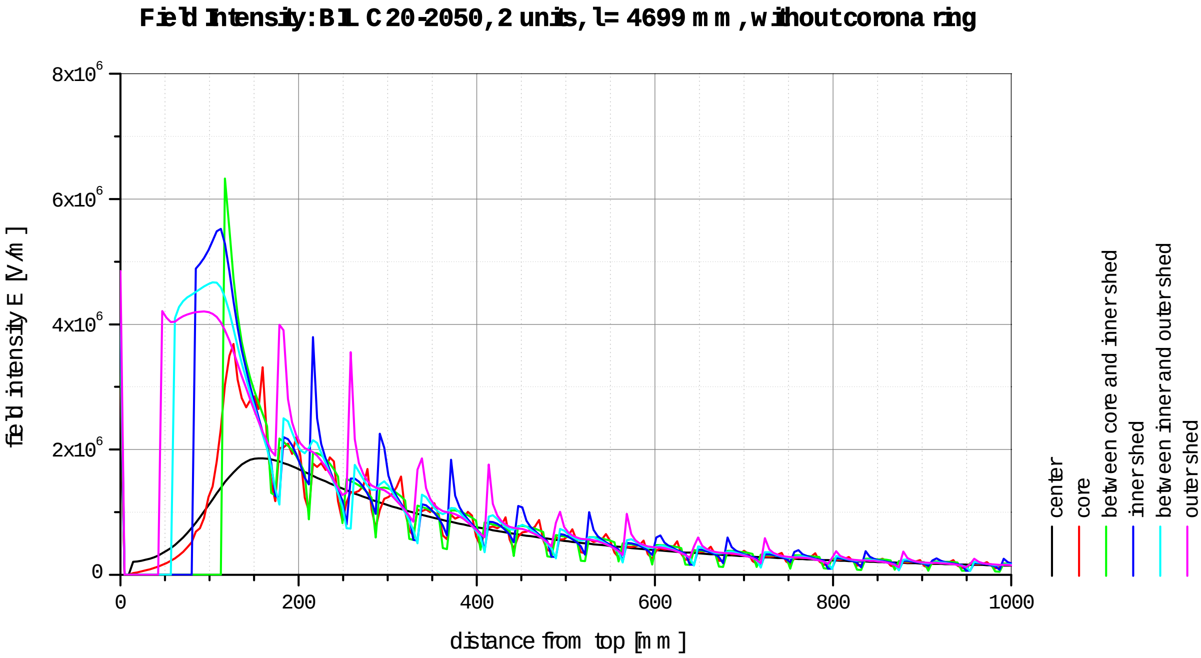


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 63: Voltage Characteristic: BIL C20-2050, 2 units, l = 4699 mm, with CR

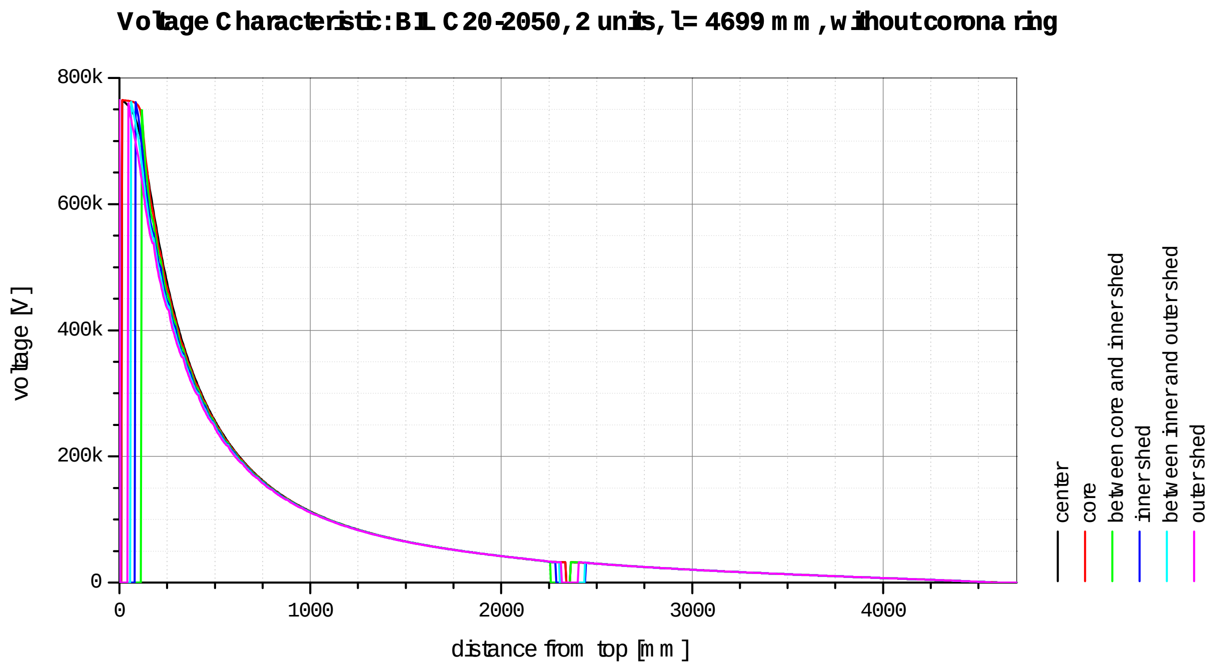


a) Course of the electric field along the whole insulator at different radial points

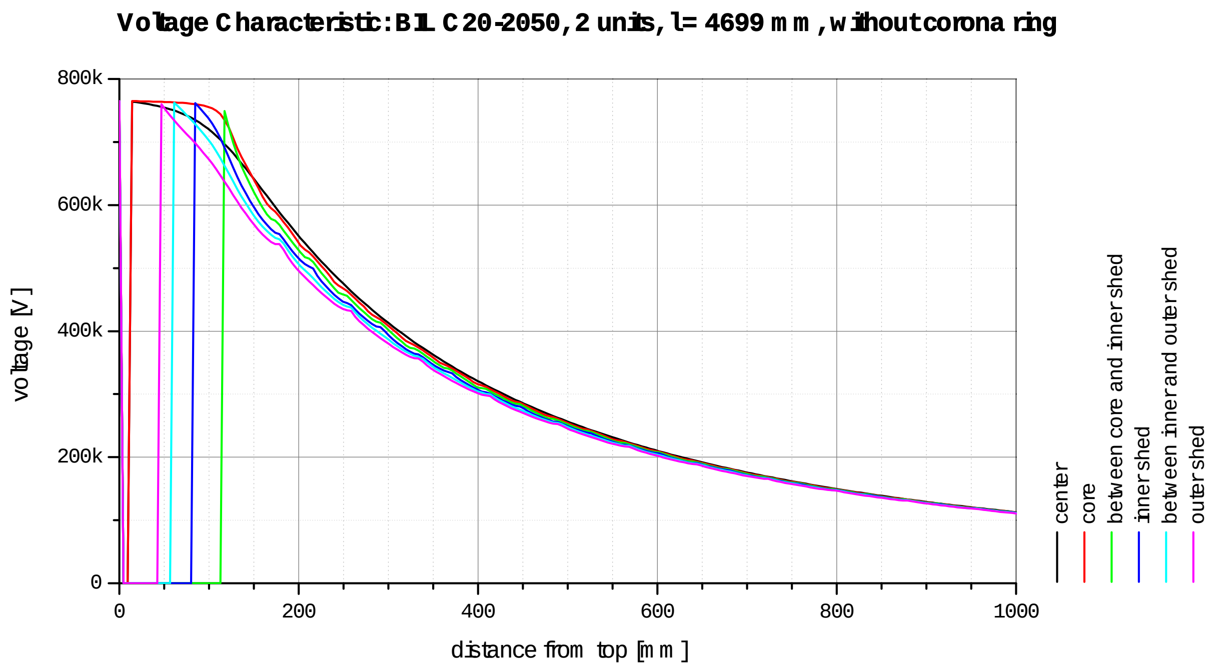


b) Course of the electric field along the first meter from the top at different radial points

Fig. 64: Field Distribution: BIL C20-2050, 2 units, l = 4699 mm, without CR

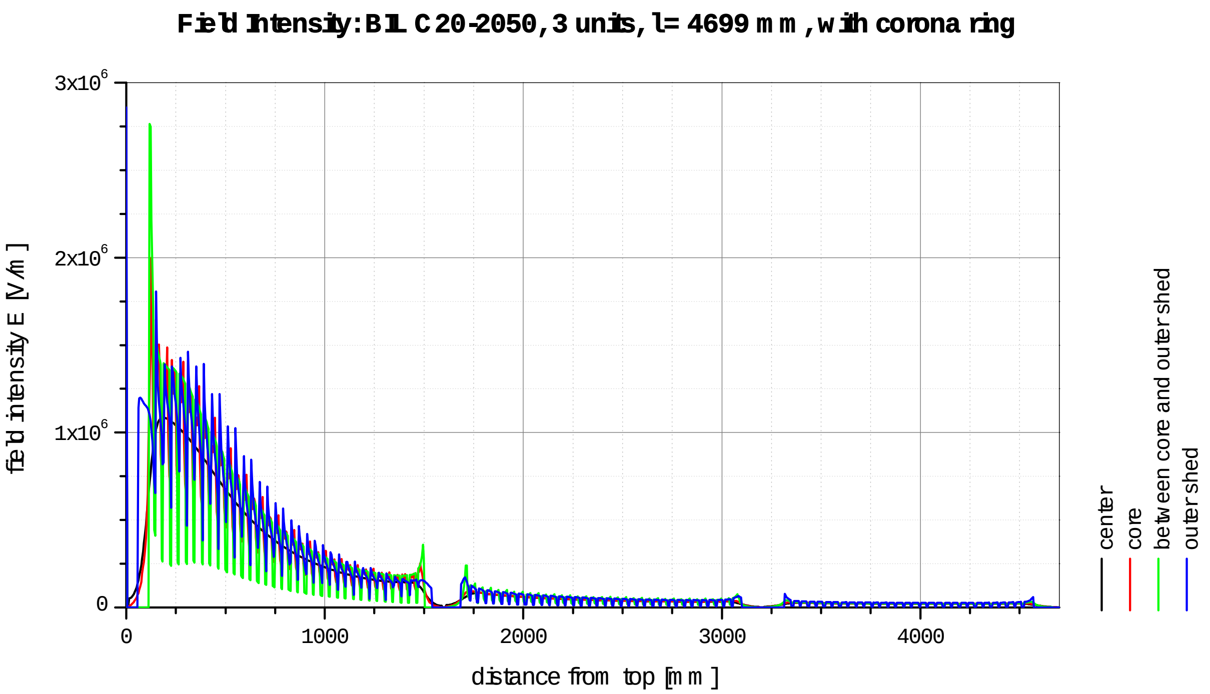


a) Voltage Characteristic along the whole insulator at different radial points

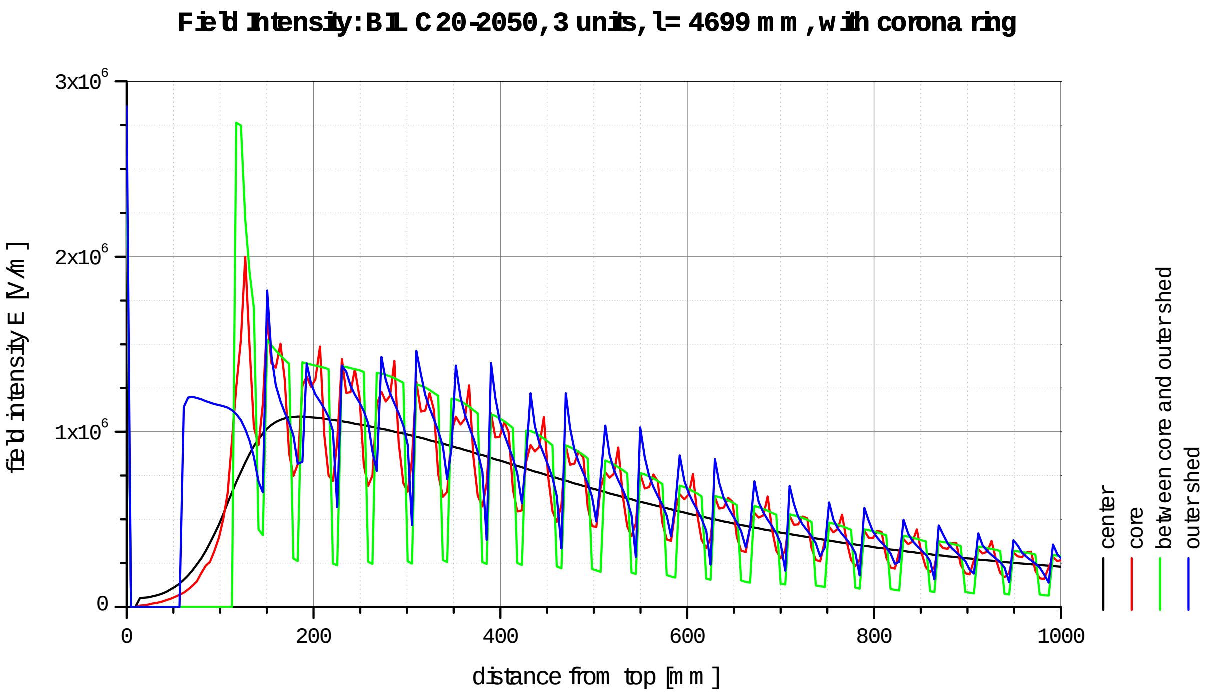


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 65: Voltage Characteristic: BIL C20-2050, 2 units, l = 4699 mm, without CR

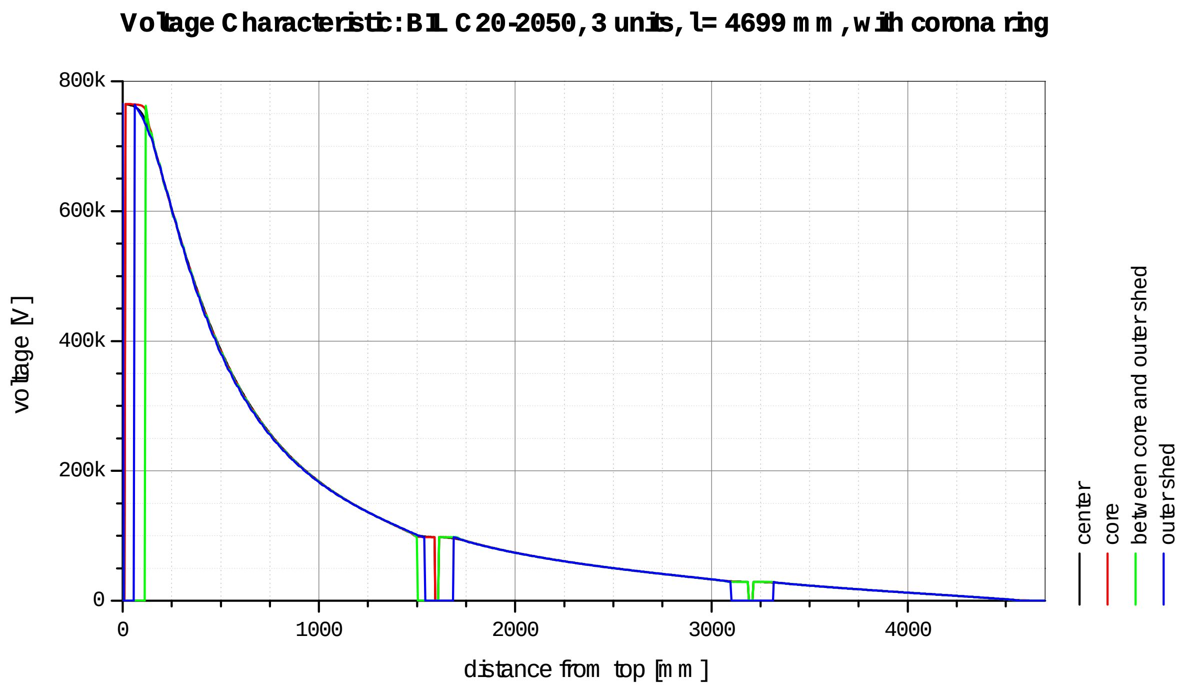


a) Course of the electric field along the whole insulator at different radial points

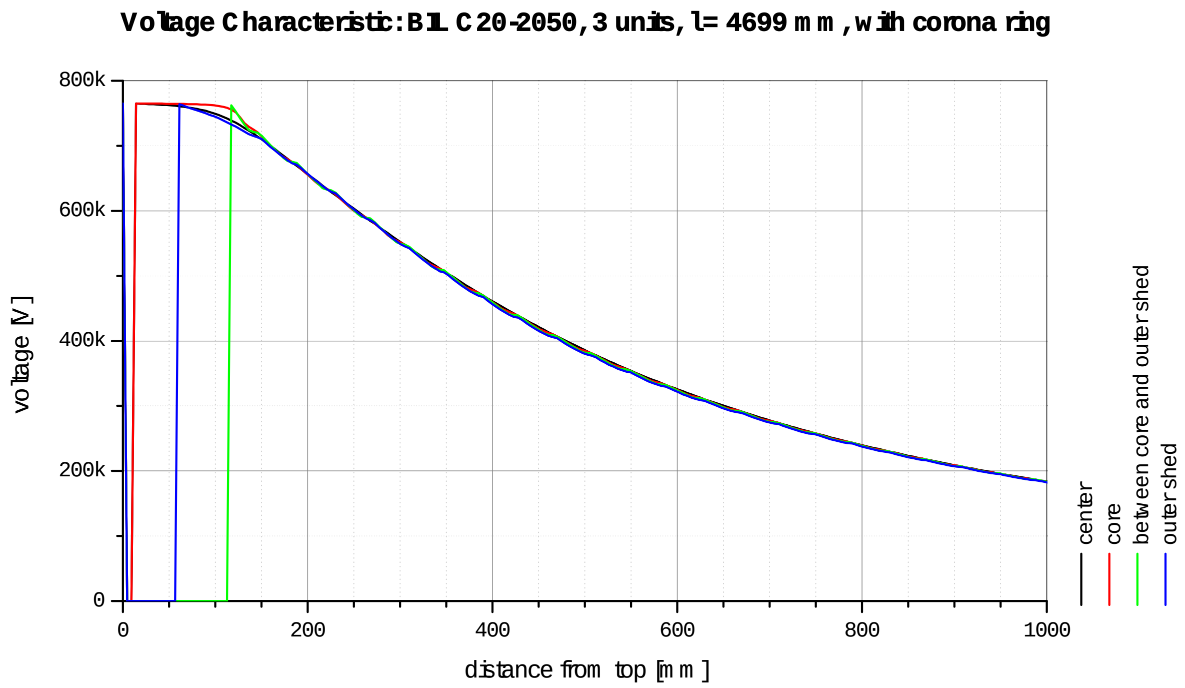


b) Course of the electric field along the first meter from the top at different radial points

Fig. 66: Field Distribution: BIL C20-2050, 3 units, l = 4699 mm, with CR

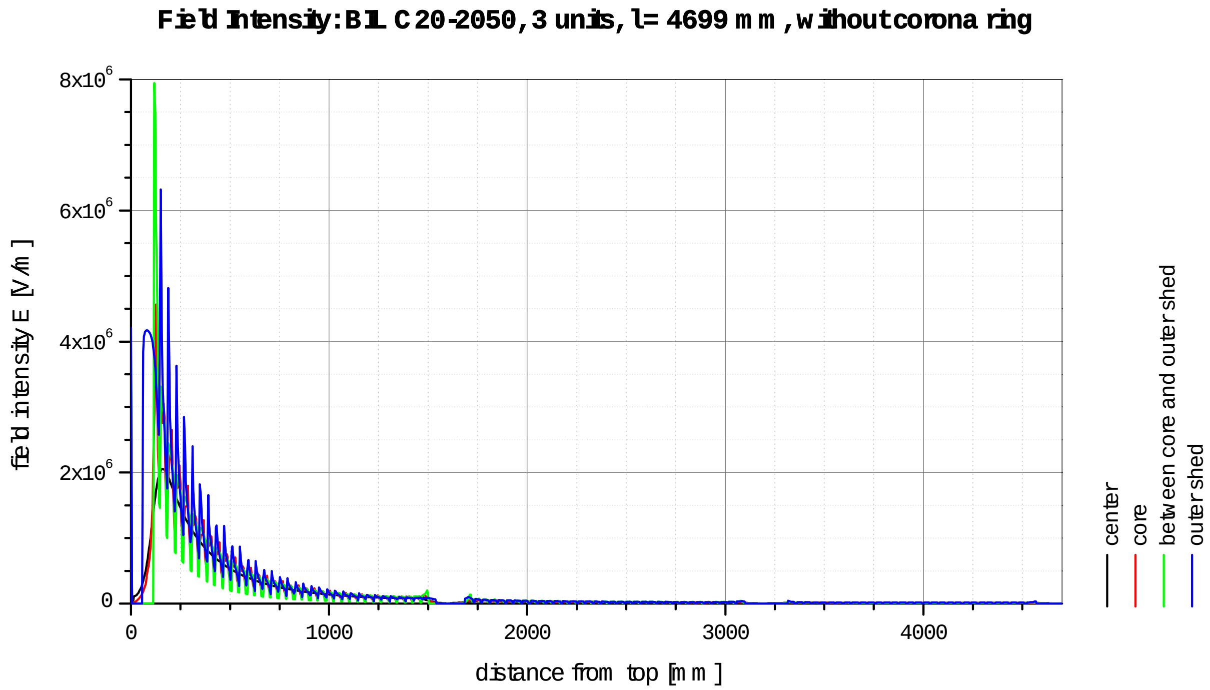


a) Voltage Characteristic along the whole insulator at different radial points

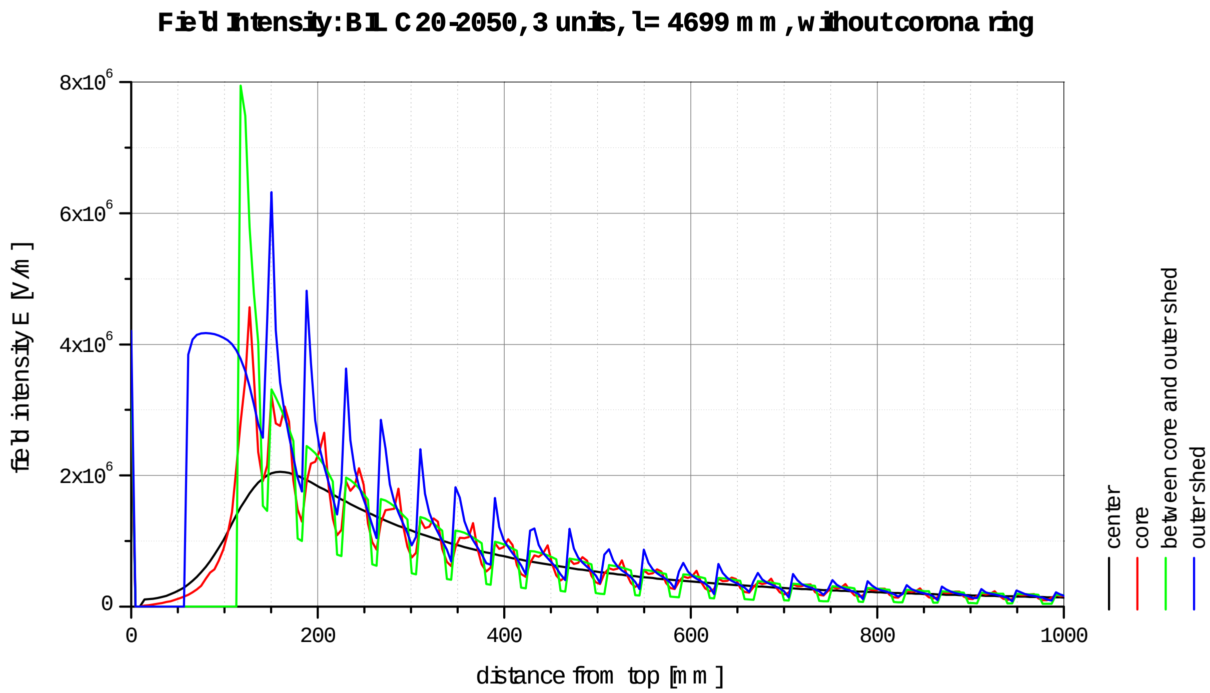


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 67: Voltage Characteristic: BIL C20-2050, 3 units, l = 4699 mm, with CR

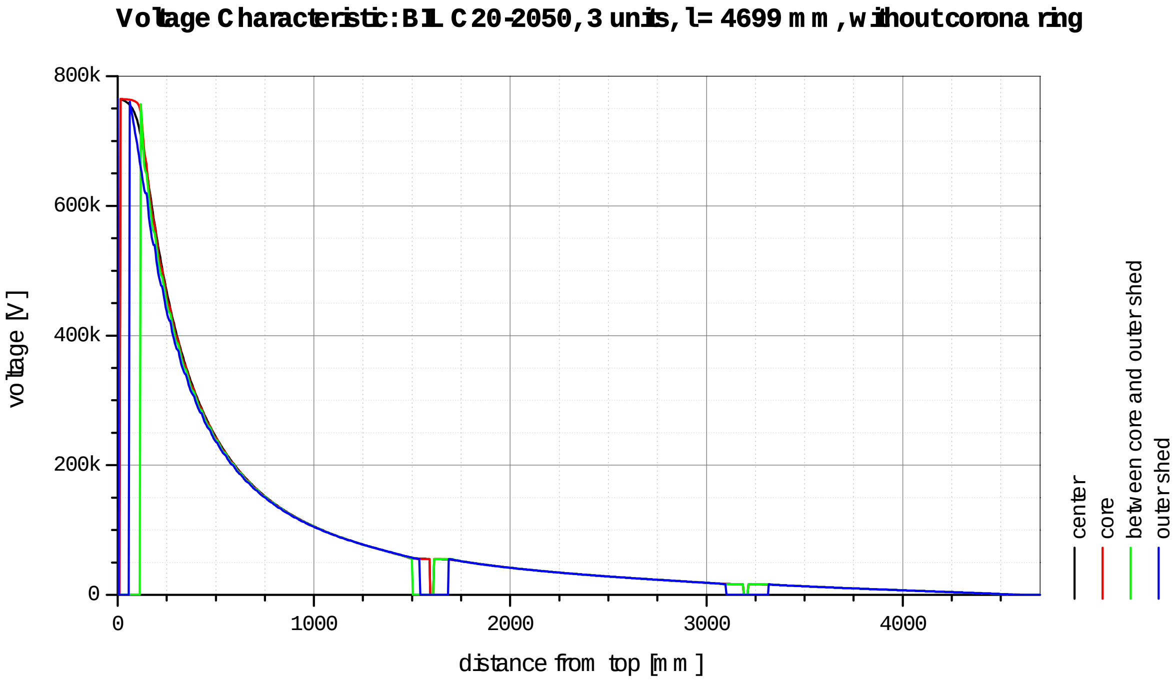


a) Course of the electric field along the whole insulator at different radial points

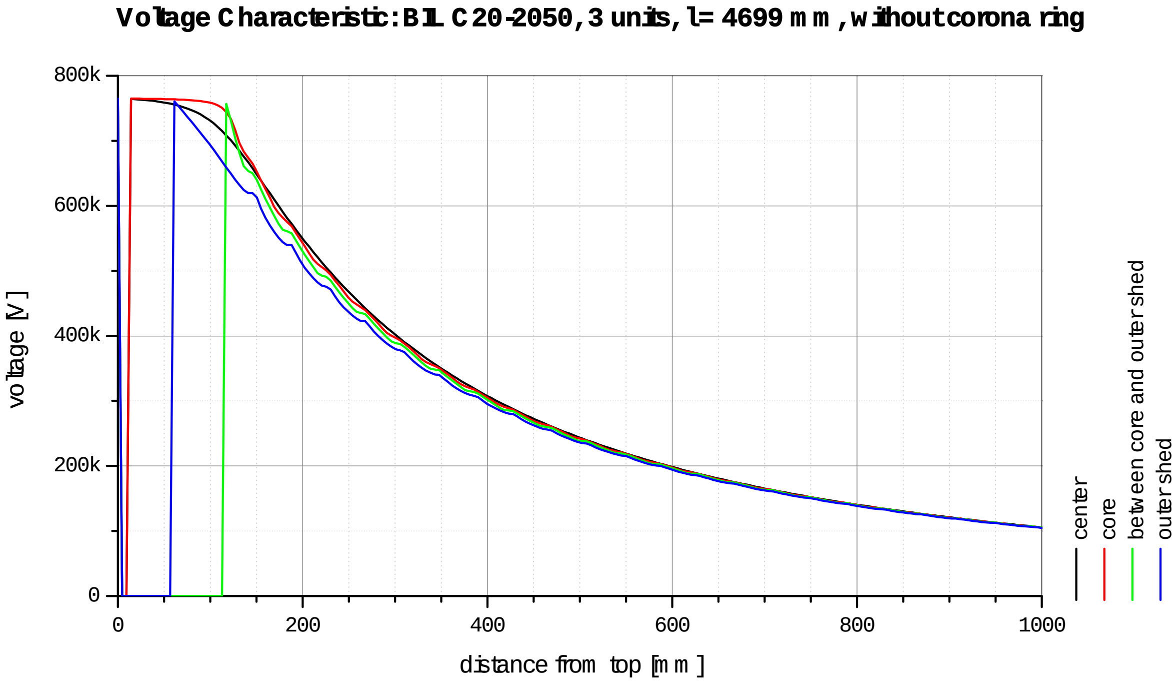


b) Course of the electric field along the first meter from the top at different radial points

Fig. 68: Field Distribution: BIL C20-2050, 3 units, l = 4699 mm, without CR

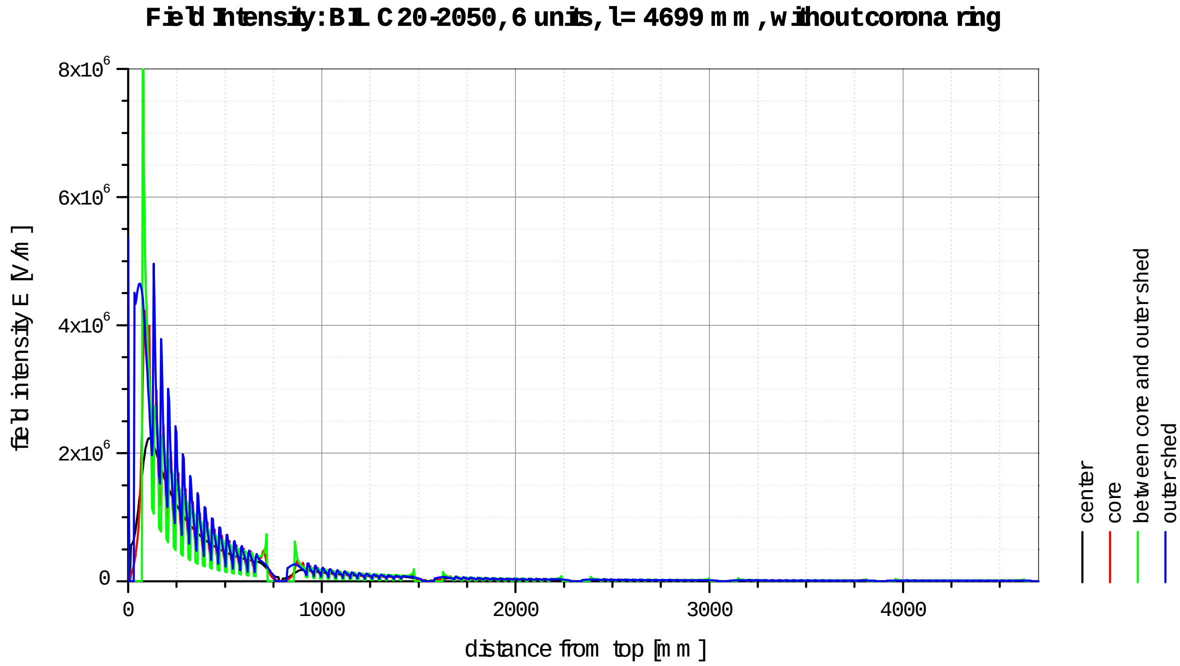


a) Voltage Characteristic along the whole insulator at different radial points

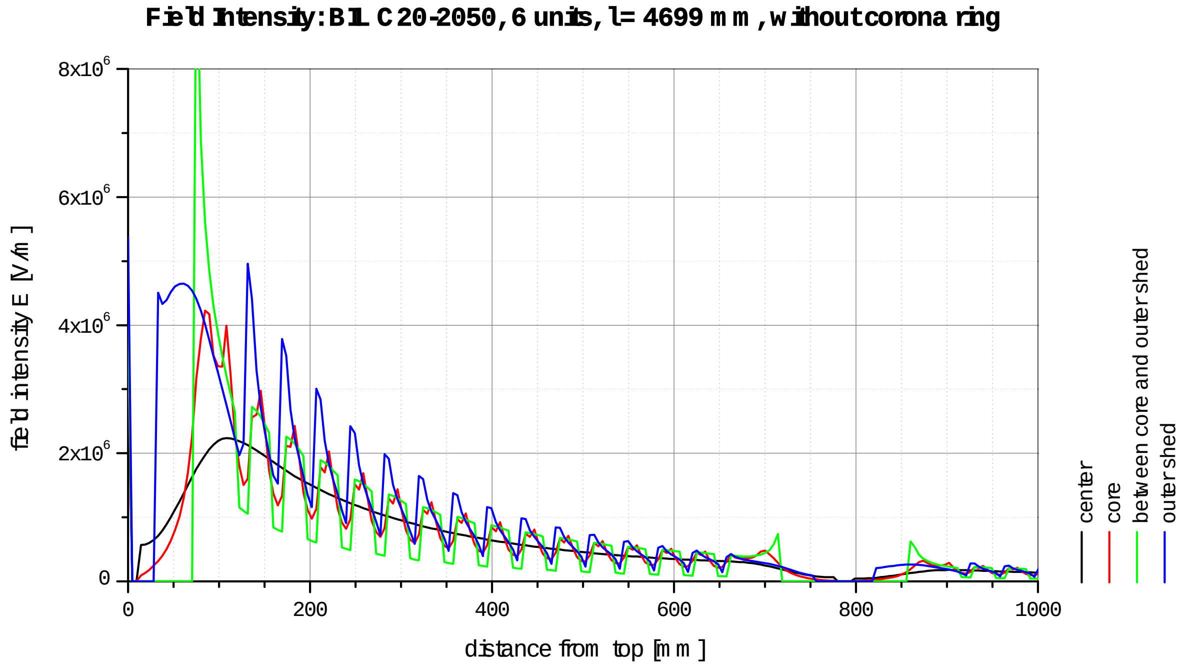


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 69: Voltage Characteristic: BIL C20-2050, 3 units, l = 4699 mm, without CR

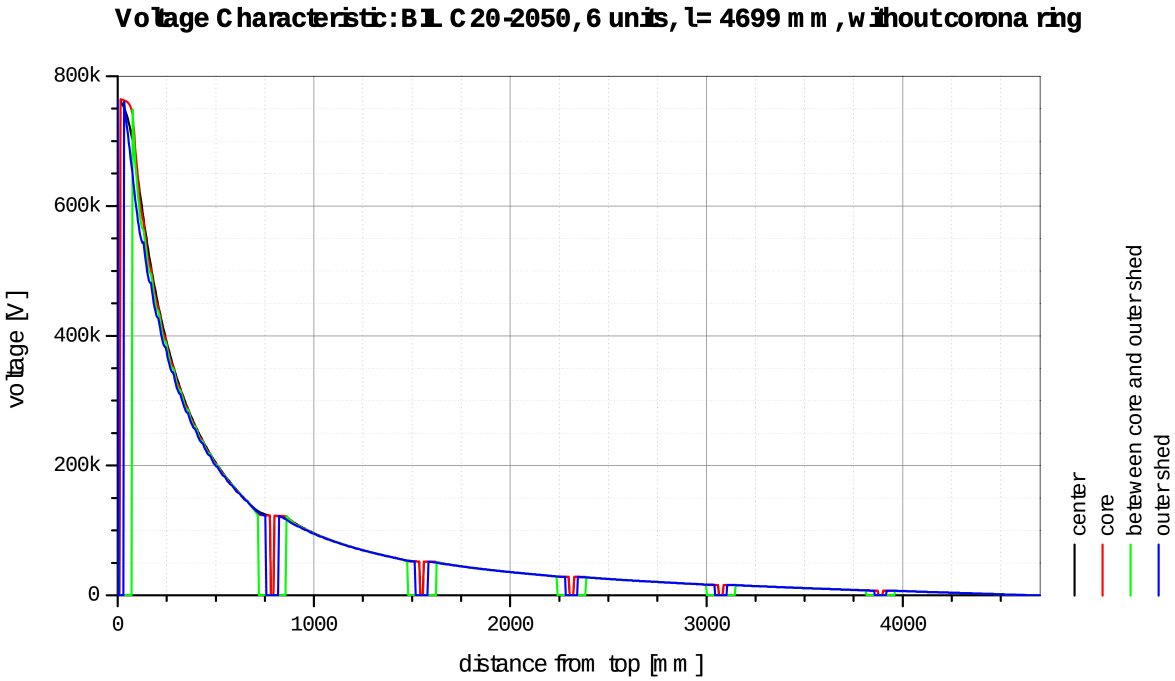


a) Course of the electric field along the whole insulator at different radial points

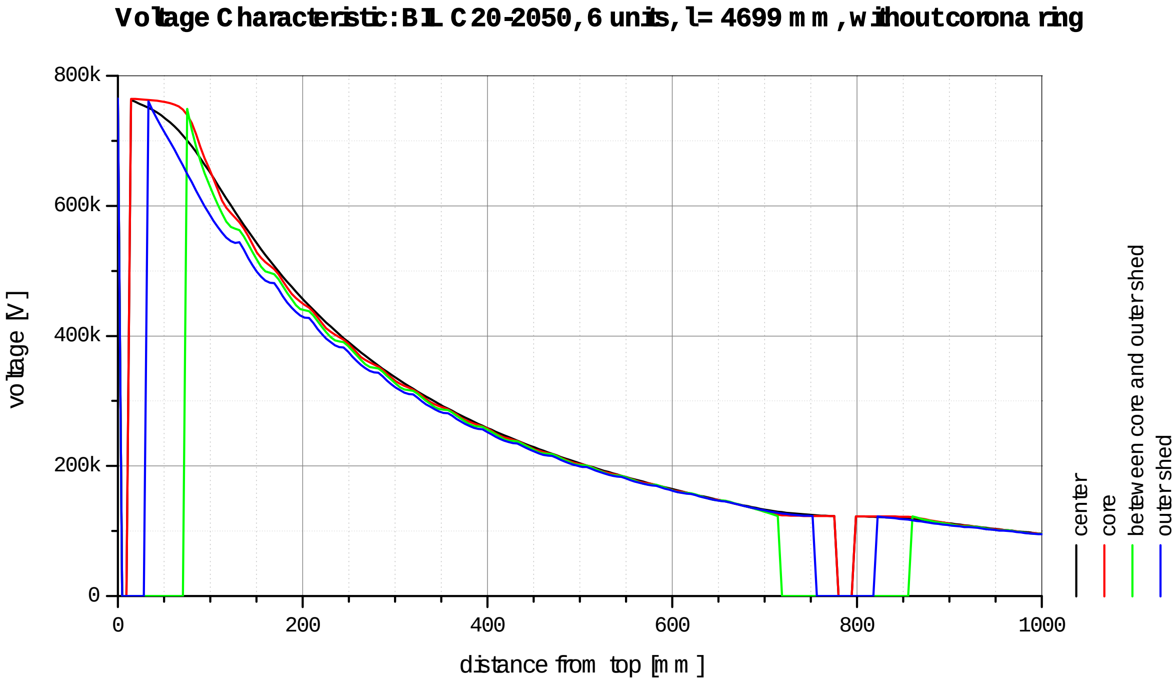


b) Course of the electric field along the first meter from the top at different radial points

Fig. 70: Field Distribution: BIL C20-2050, 6 units, l = 4699 mm, without CR



a) Voltage Characteristic along the whole insulator at different radial points

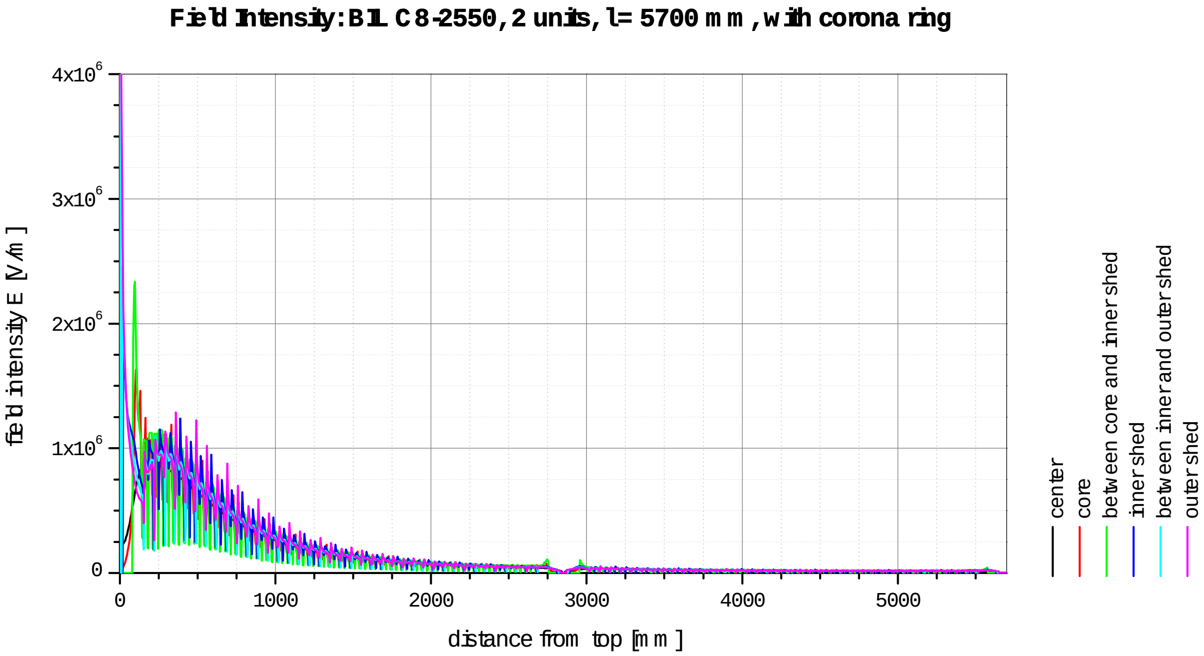


b) Voltage Characteristic along the first meter from the top at different radial points

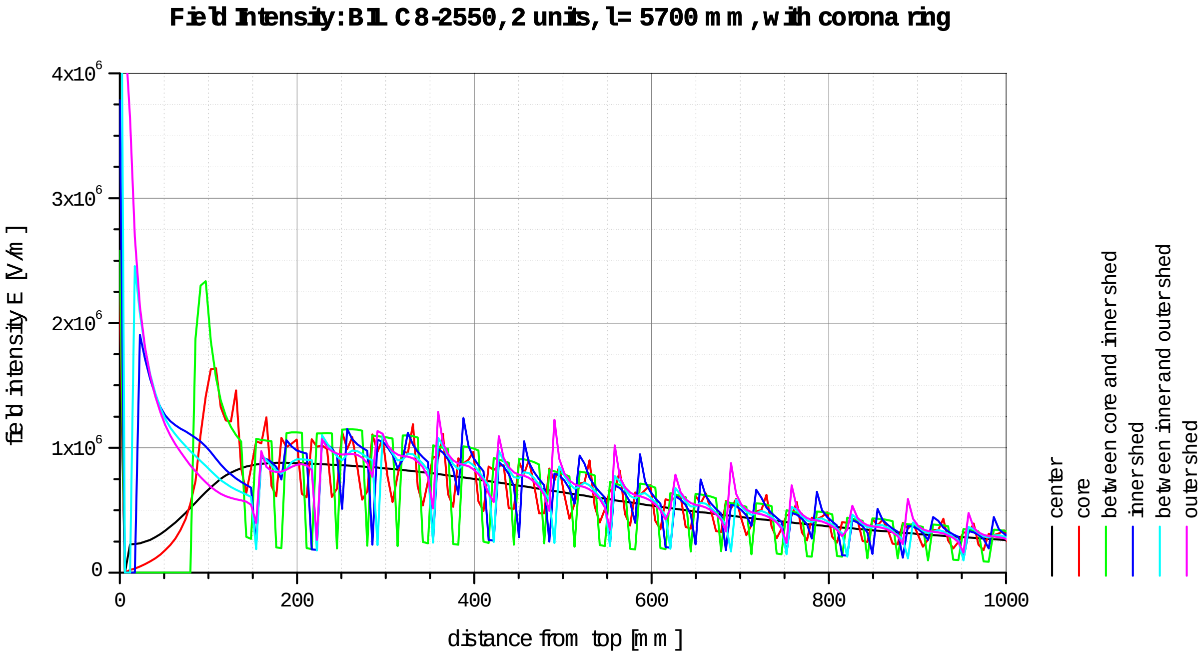
Fig. 71: Voltage Characteristic: BIL C20-2050, 6 units, l = 4699 mm, without CR

A.6 Electrostatic Field Simualtions for BIL 2550 insulators

In the following section the results of the electrostatic field simulations for insulator arrangements with a dry lightning impulse withstand voltage of 2550 kV can be found. All arrangements have been simulated at a system voltage of 800 kV. The graphs show the progression of the field intensity and voltage characteristic of the single insulator arrangement at different radial lines across the whole insulator.

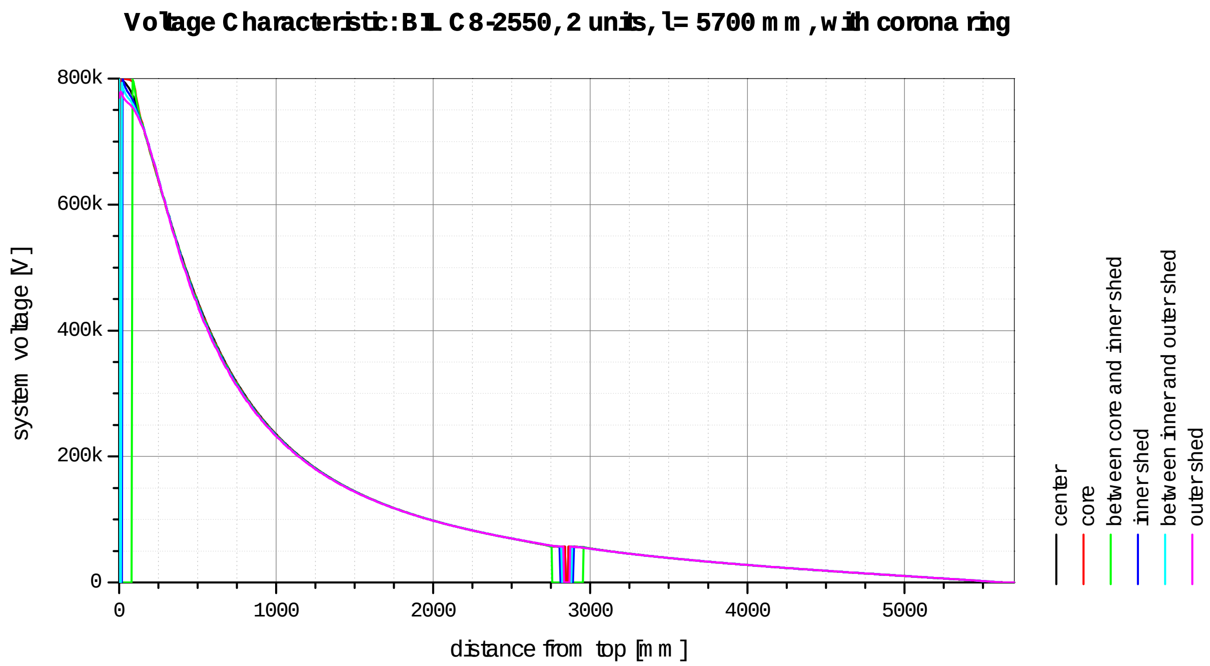


a) Course of the electric field along the whole insulator at different radial points

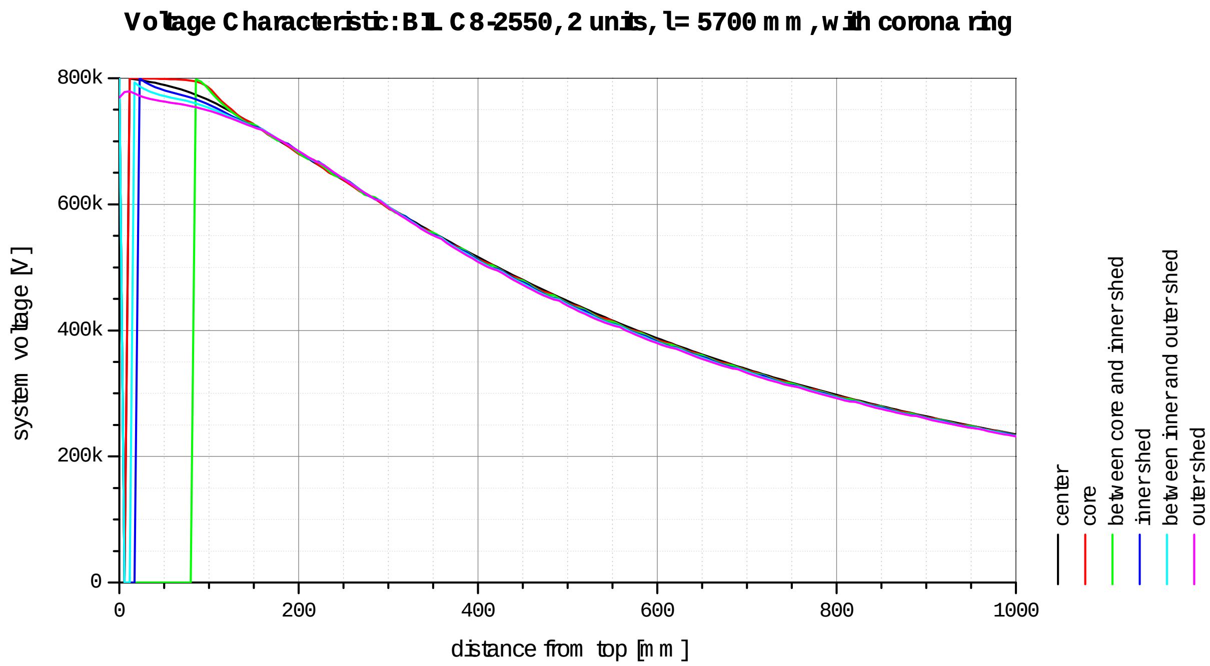


b) Course of the electric field along the first meter from the top at different radial points

Fig. 72: Field Distribution: BIL C20-2550, 2 units, l = 5700 mm, with CR

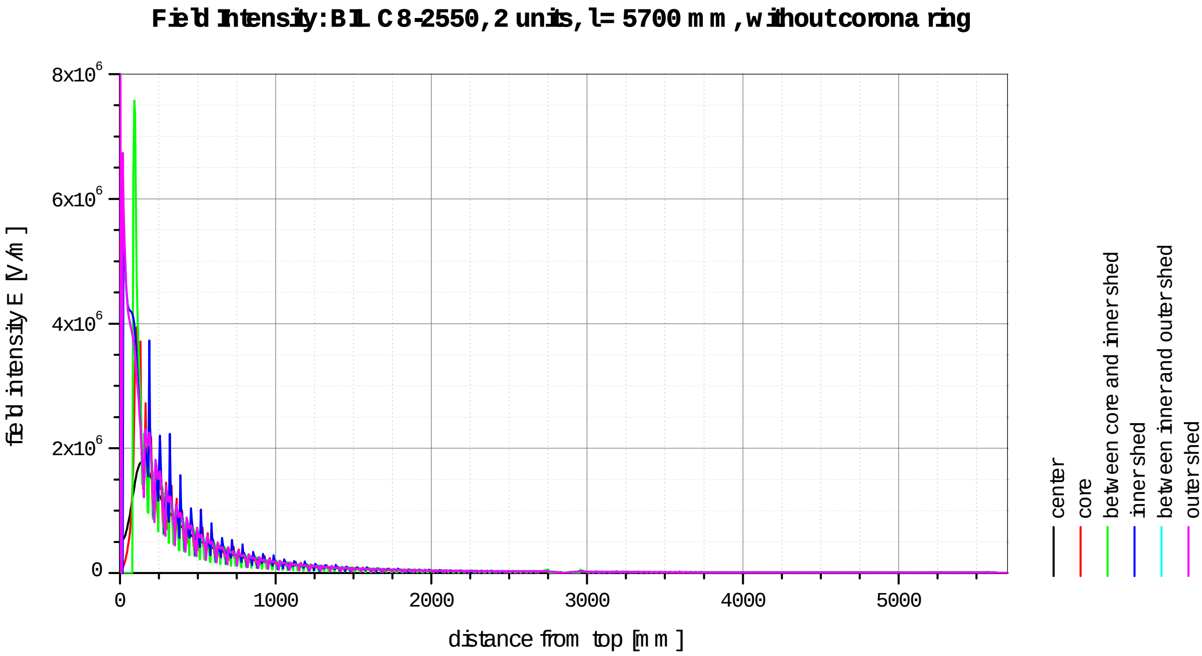


a) Voltage Characteristic along the whole insulator at different radial points

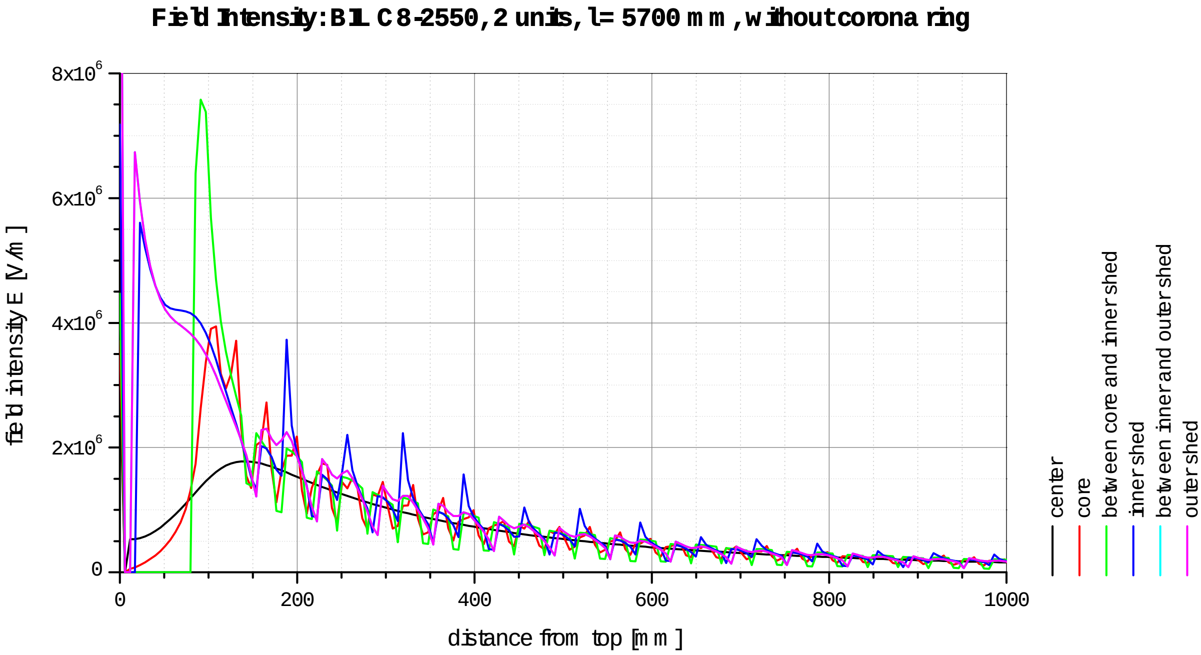


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 73: Voltage Characteristic: BIL C20-2550, 2 units, l = 5700 mm, with CR

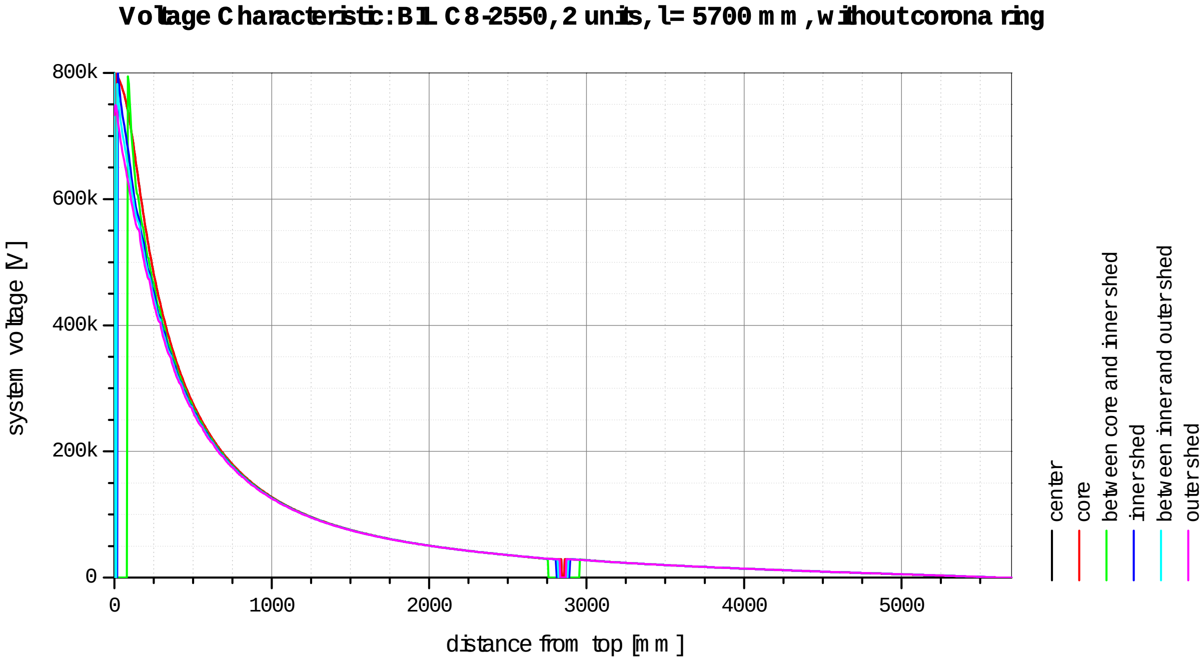


a) Course of the electric field along the whole insulator at different radial points

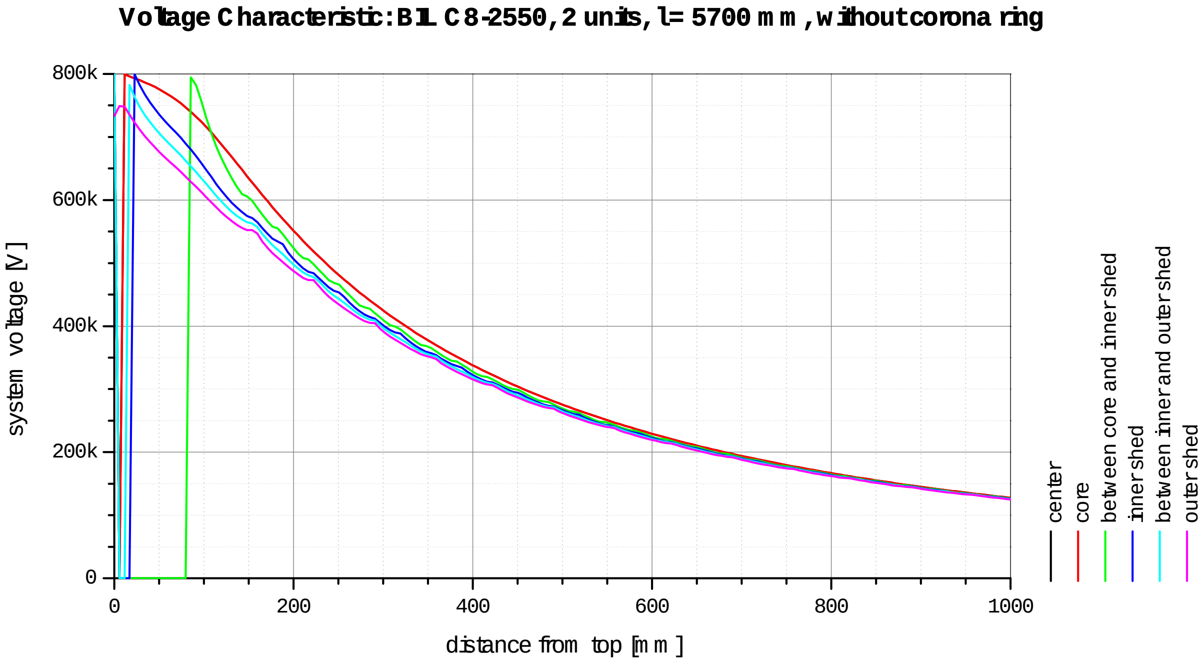


b) Course of the electric field along the first meter from the top at different radial points

Fig. 74: Field Distribution: BIL C20-2550, 2 units, l = 5700 mm, without CR

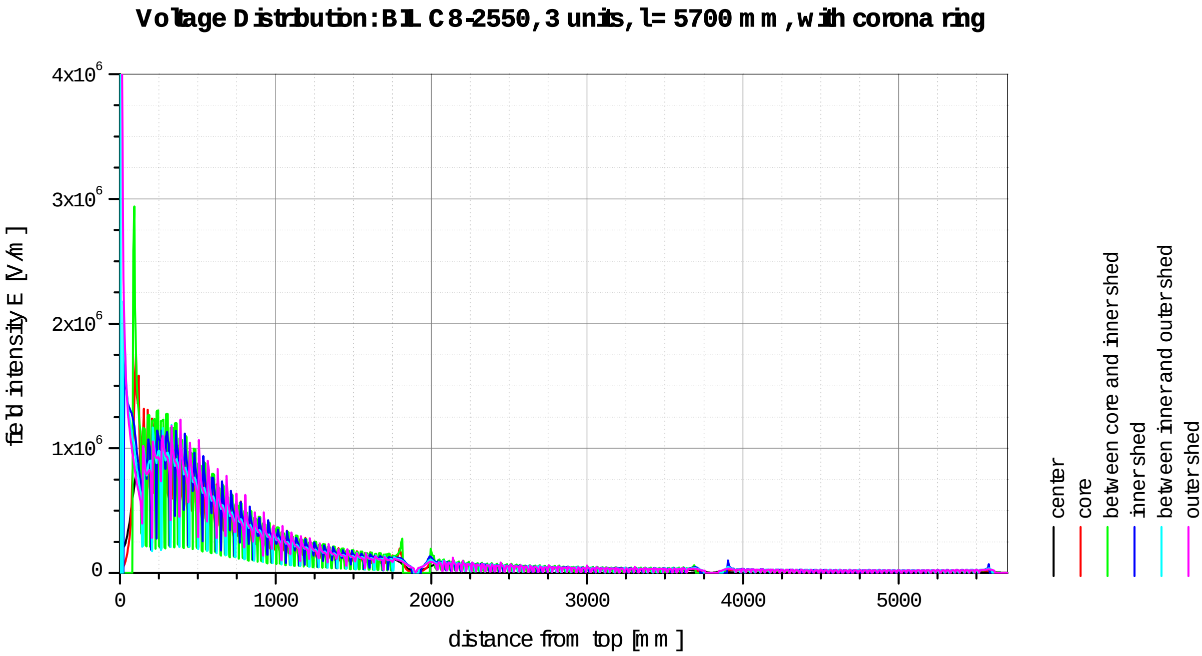


a) Voltage Characteristic along the whole insulator at different radial points

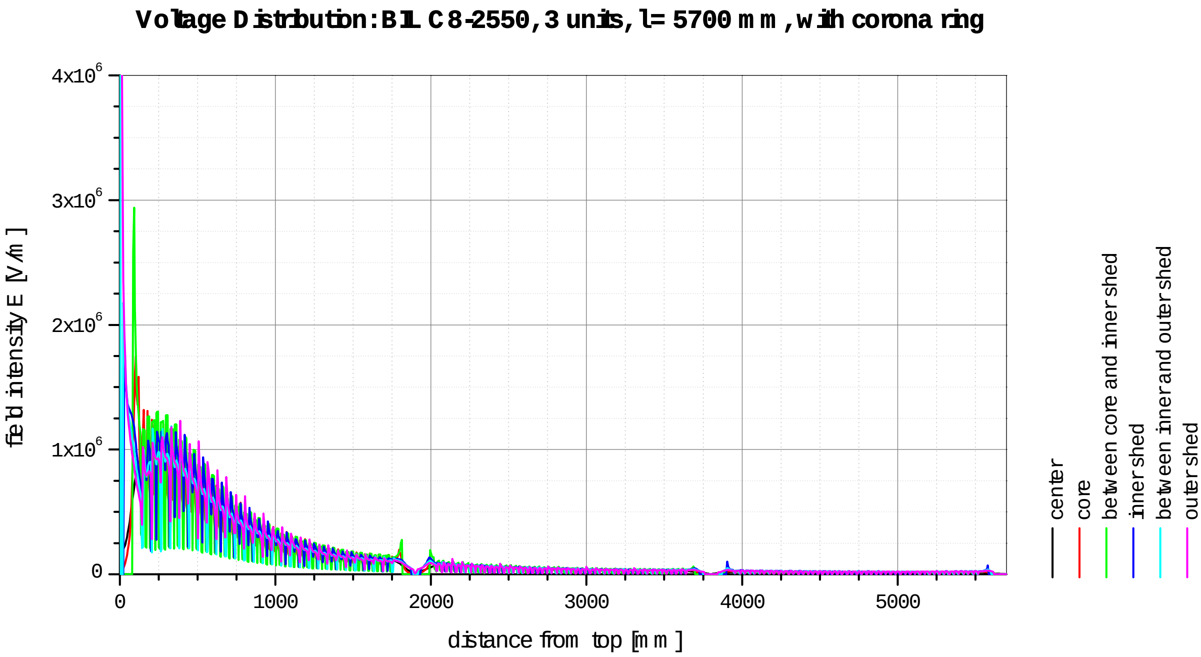


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 75: Voltage Characteristic: BIL C20-2550, 2 units, l = 5700 mm, without CR

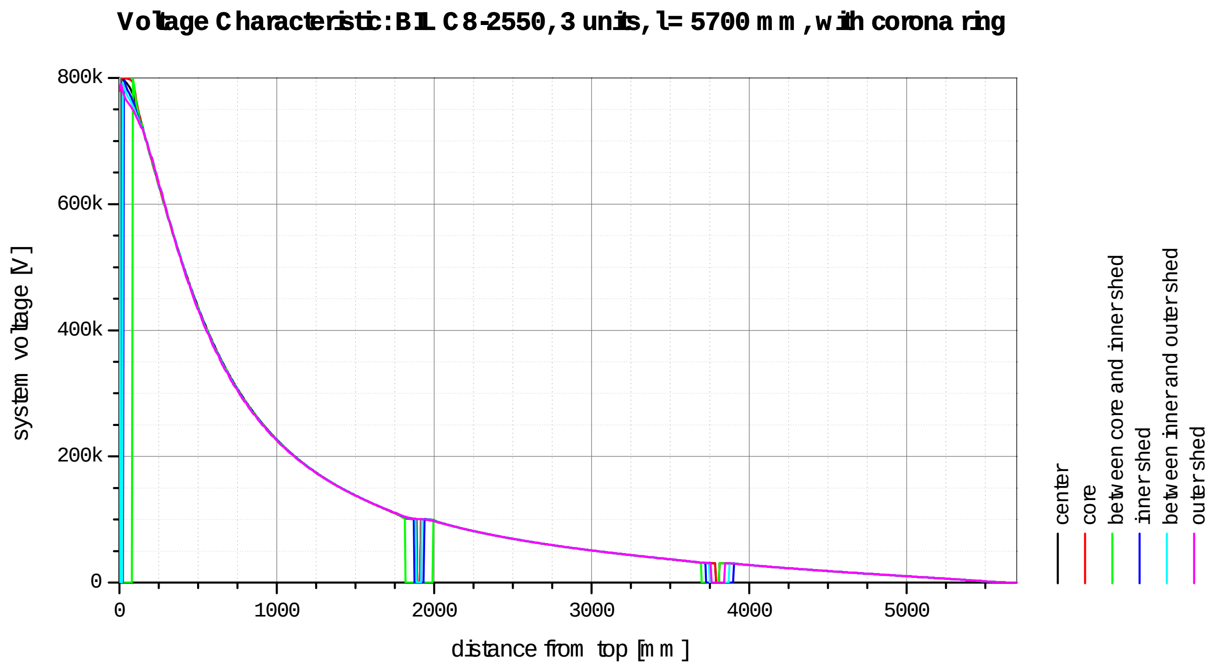


a) Course of the electric field along the whole insulator at different radial points

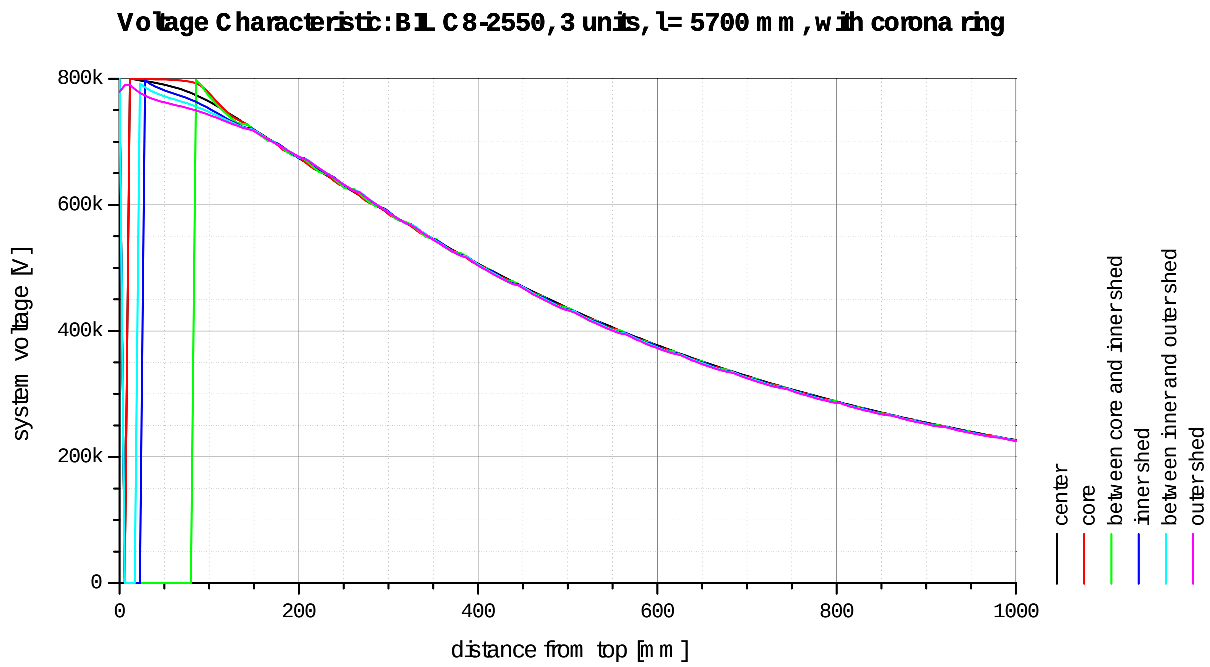


b) Course of the electric field along the first meter from the top at different radial points

Fig. 76: Field Distribution: BIL C8-2550, 3 units, l = 5700 mm, with CR

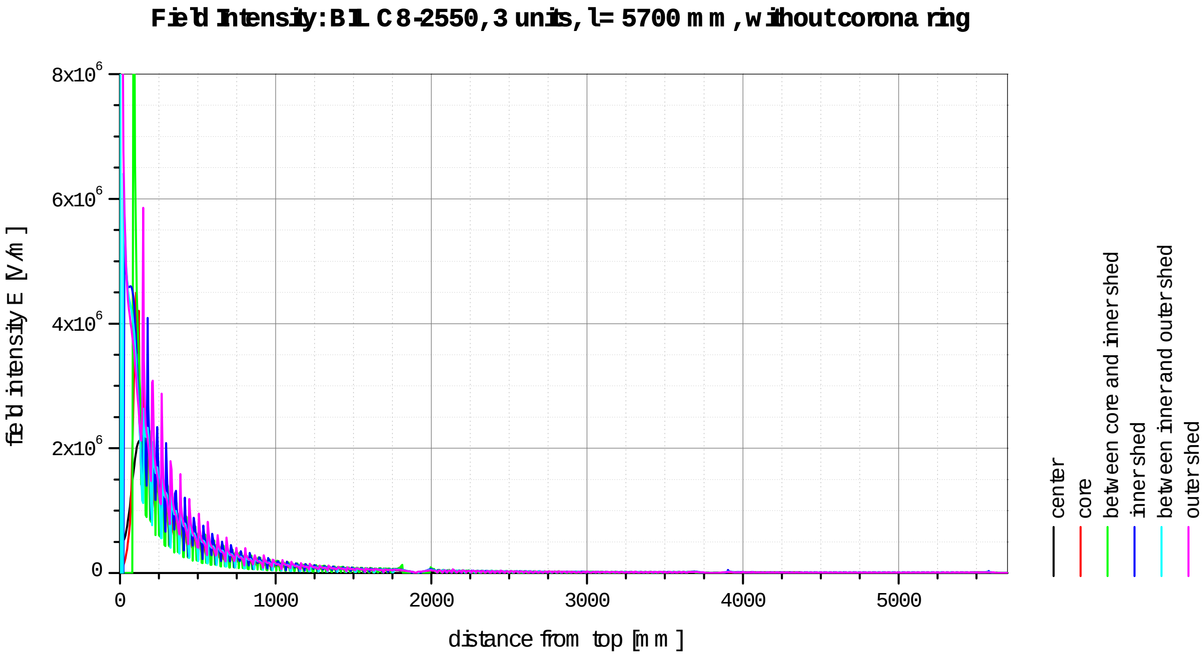


a) Voltage Characteristic along the whole insulator at different radial points

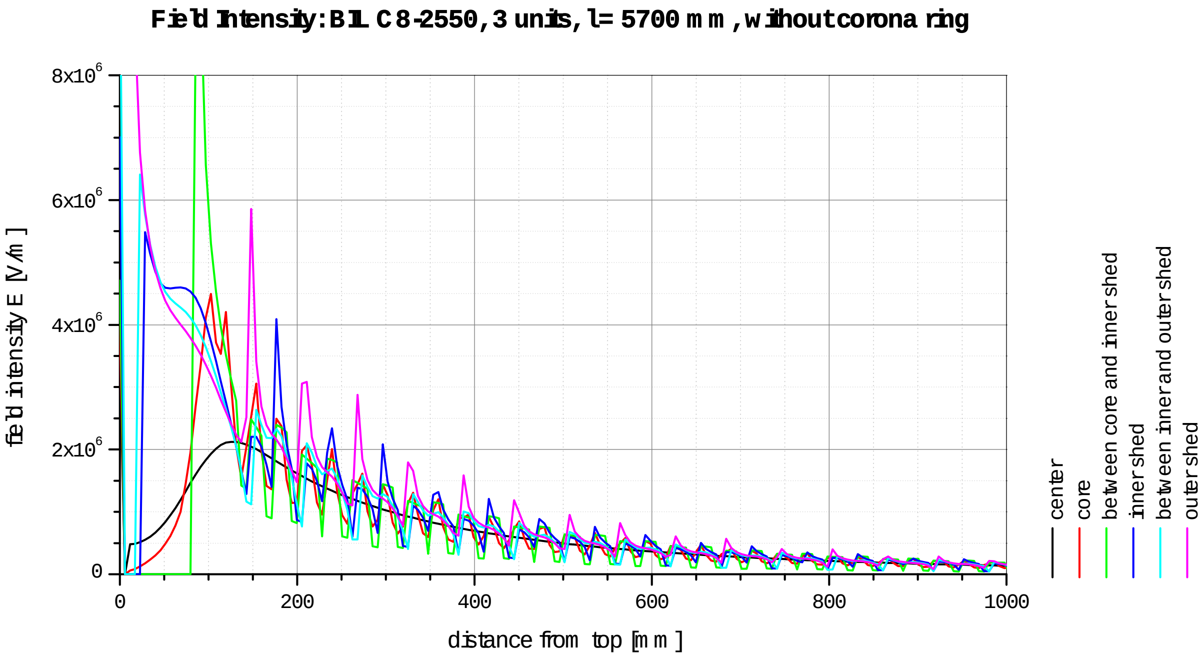


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 77: Voltage Characteristic: BIL C8-2550, 3 units, l = 5700 mm, with CR

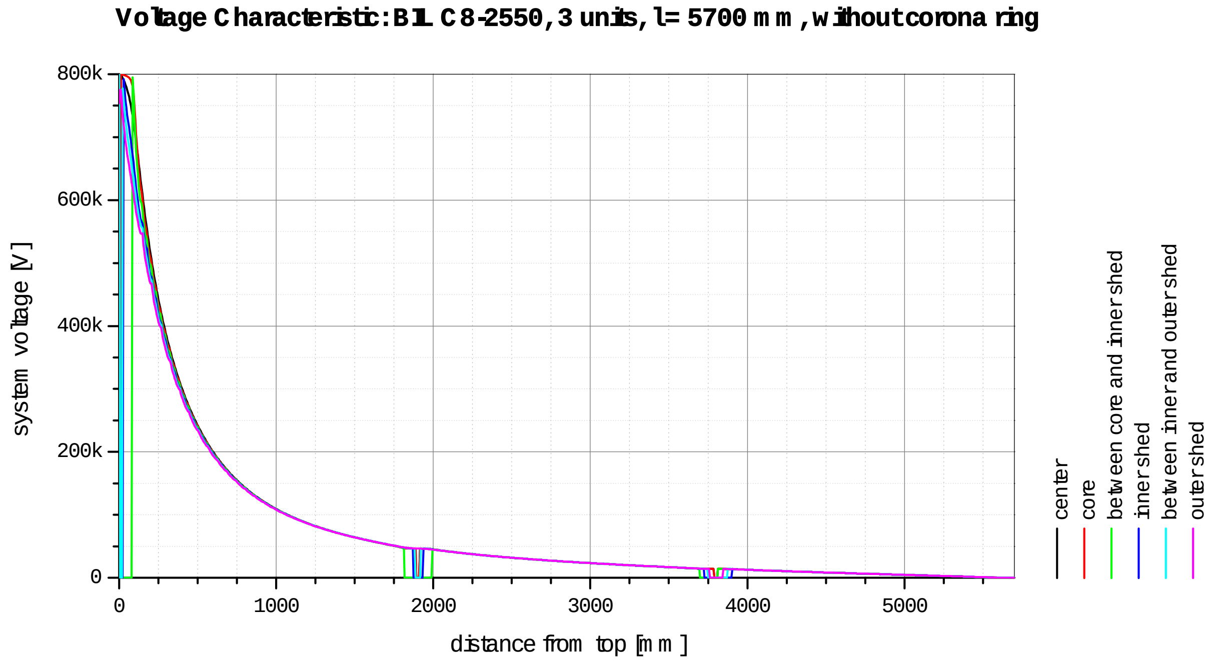


a) Course of the electric field along the whole insulator at different radial points

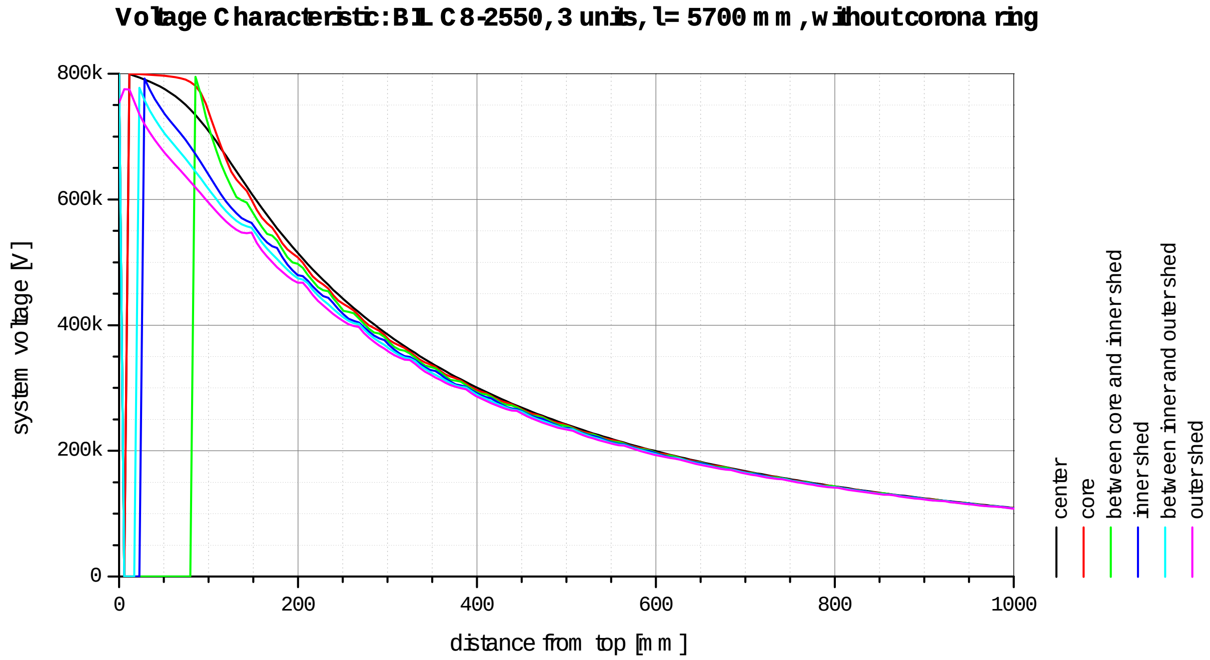


b) Course of the electric field along the first meter from the top at different radial points

Fig. 78: Field Distribution: BIL C8-2550, 3 units, l = 5700 mm, without CR

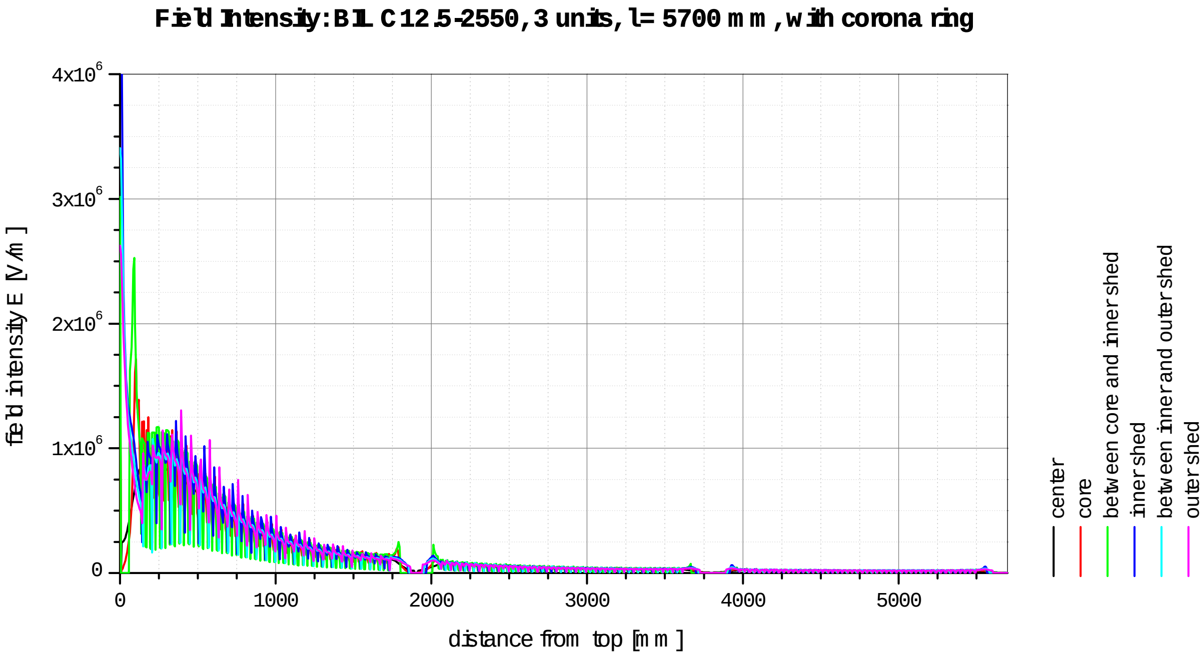


a) Voltage Characteristic along the whole insulator at different radial points

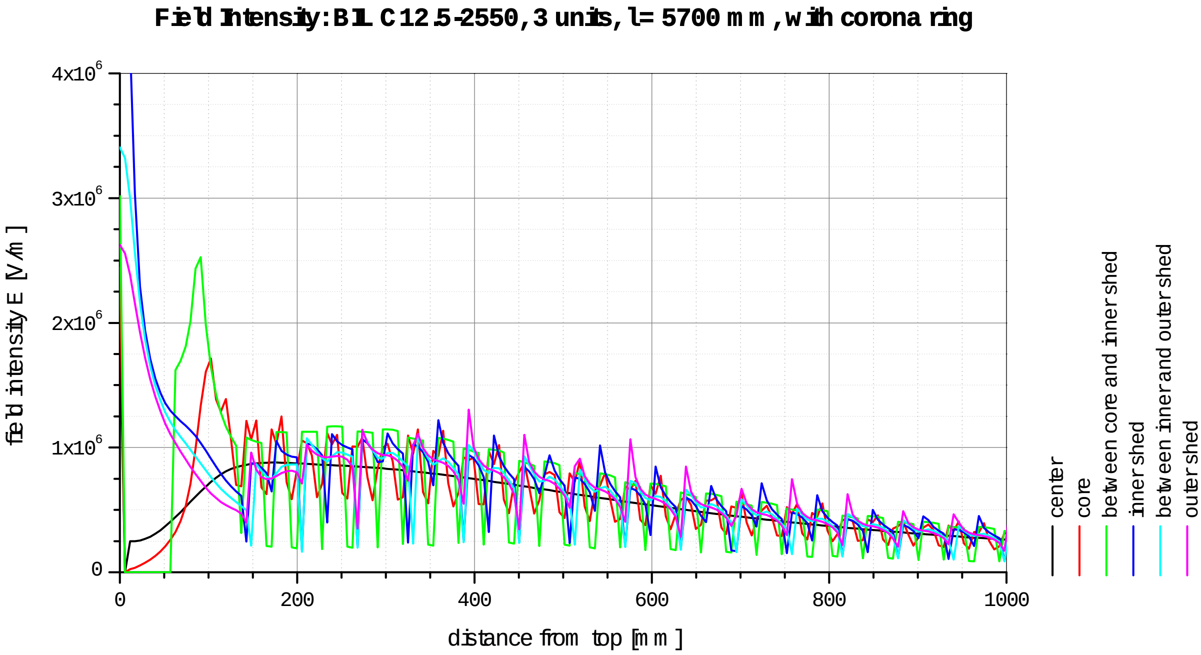


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 79: Voltage Characteristic: BIL C8-2550, 3 units, l = 5700 mm, without CR

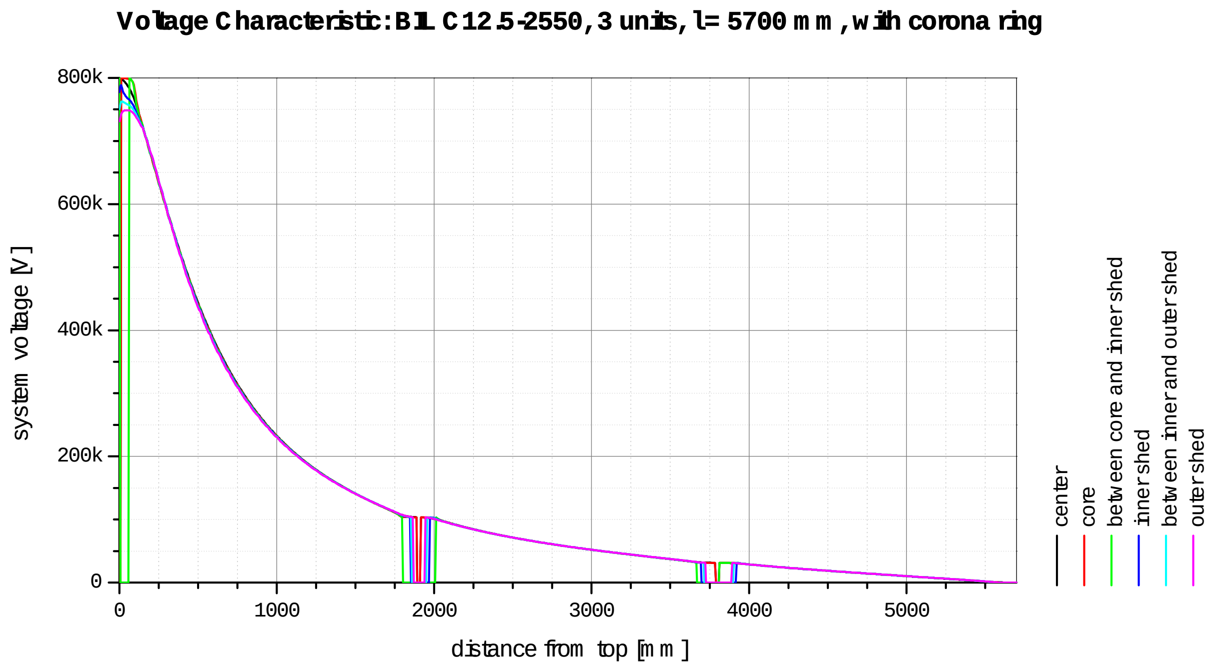


a) Course of the electric field along the whole insulator at different radial points

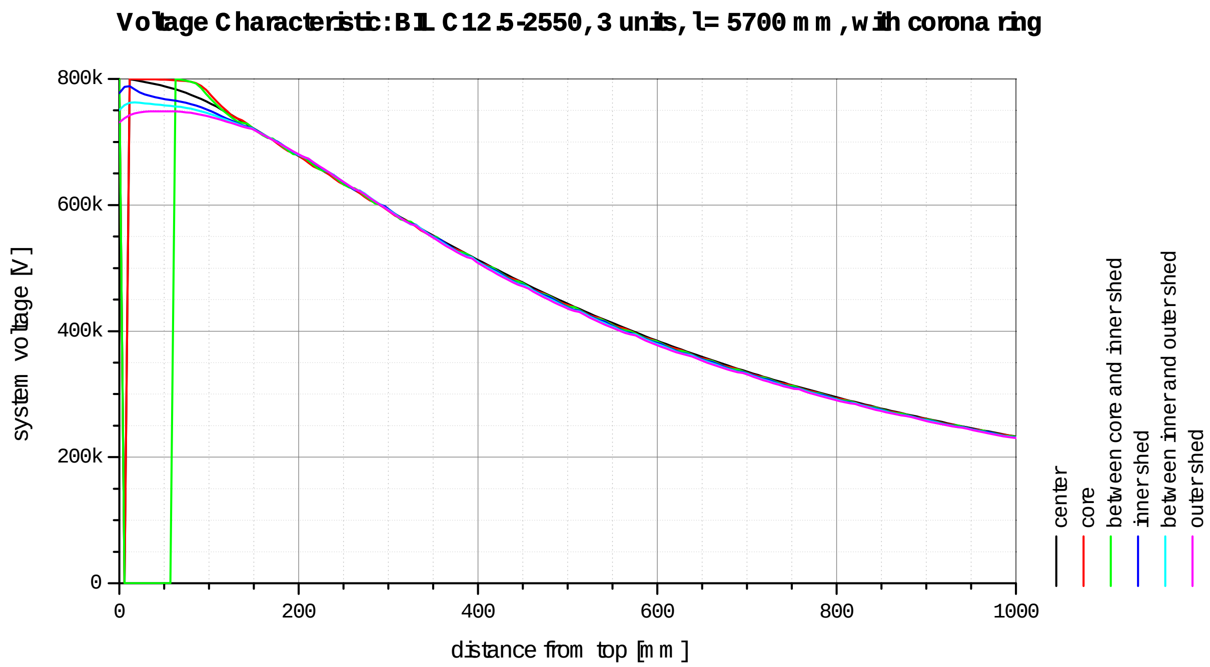


b) Course of the electric field along the first meter from the top at different radial points

Fig. 80: Field Distribution: BIL C12.5-2550, 3 units, l = 5700 mm, with CR

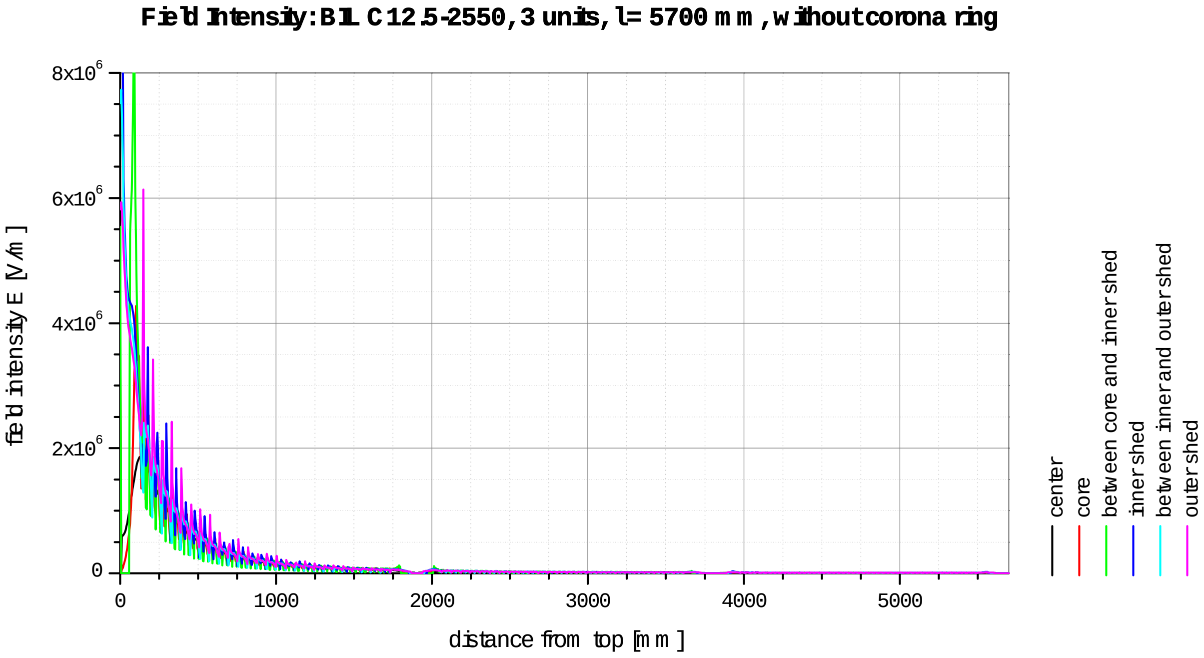


a) Voltage Characteristic along the whole insulator at different radial points

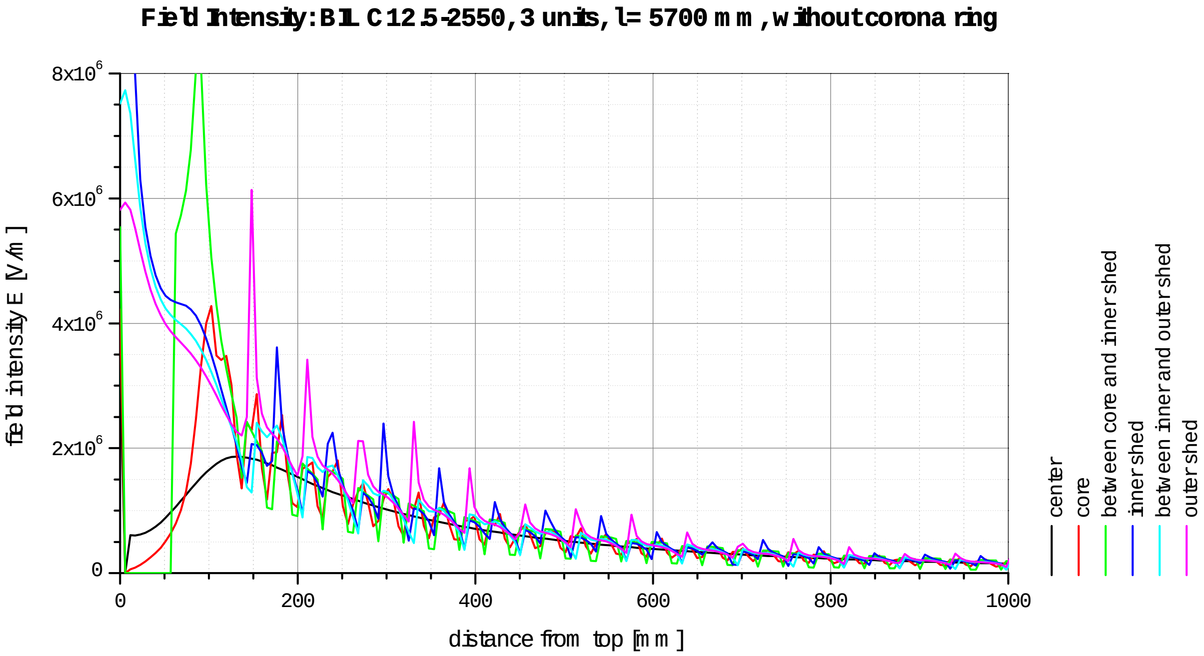


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 81: Voltage Characteristic: BIL C12.5-2550, 3 units, l = 5700 mm, with CR

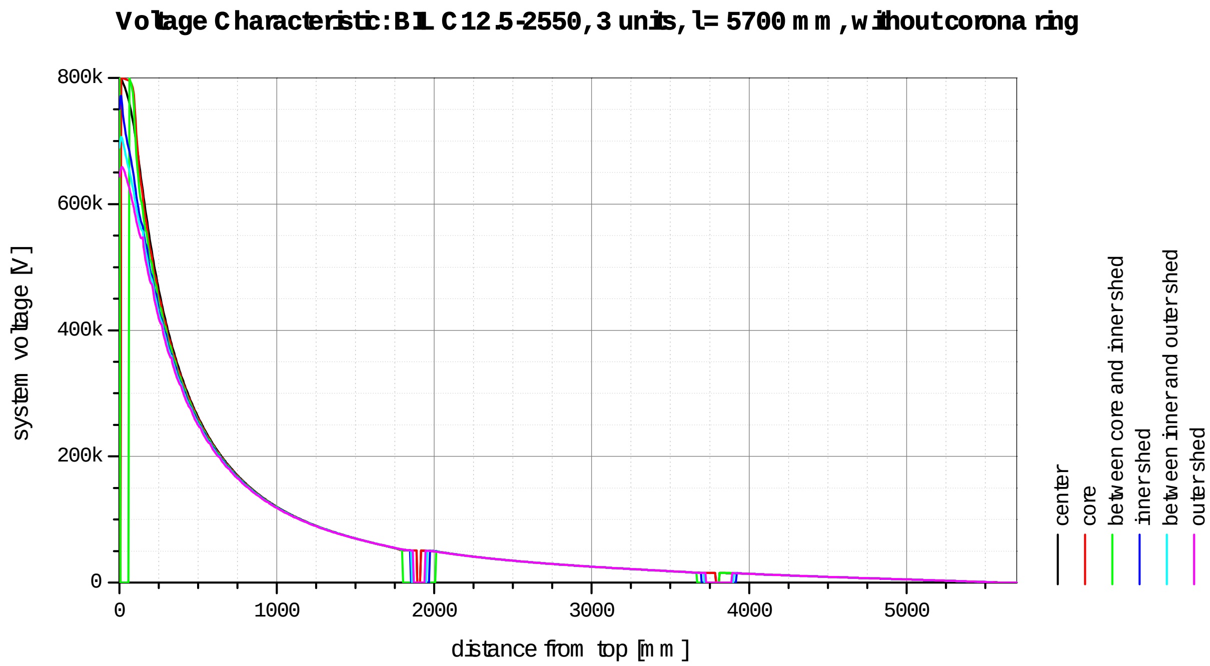


a) Course of the electric field along the whole insulator at different radial points

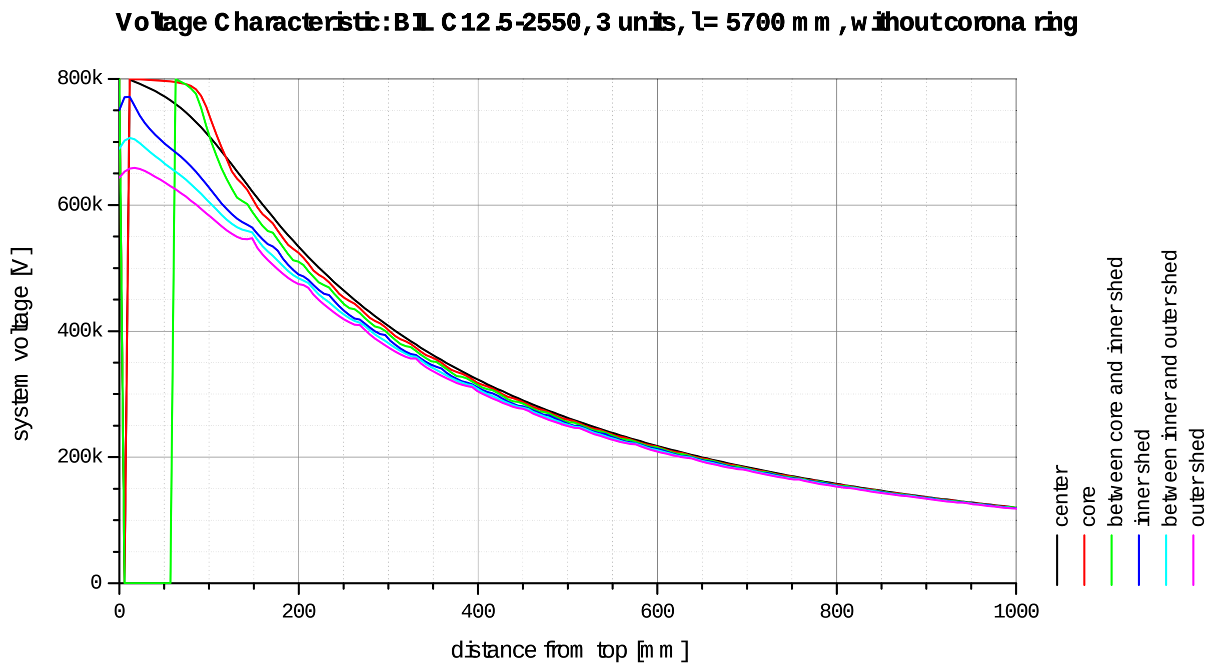


b) Course of the electric field along the first meter from the top at different radial points

Fig. 82: Field Distribution: BIL C12.5-2550, 3 units, l = 5700 mm, without CR

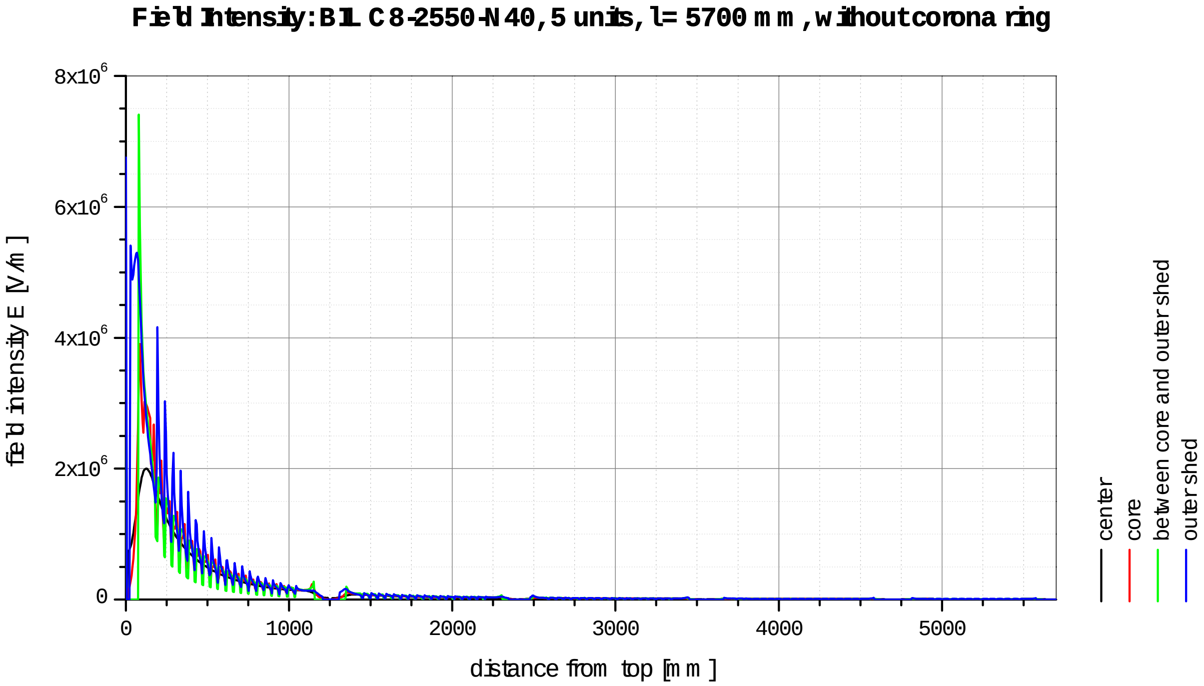


a) Voltage Characteristic along the whole insulator at different radial points

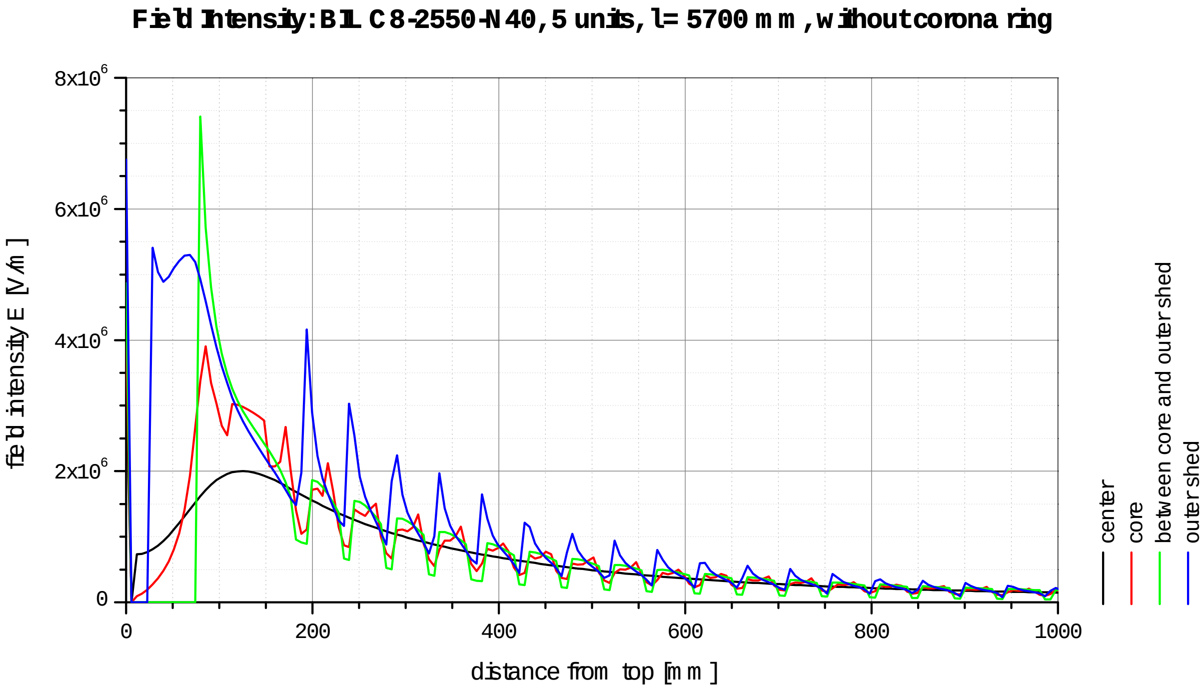


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 83: Voltage Characteristic: BIL C12.5-2550, 3 units, l = 5700 mm, without CR

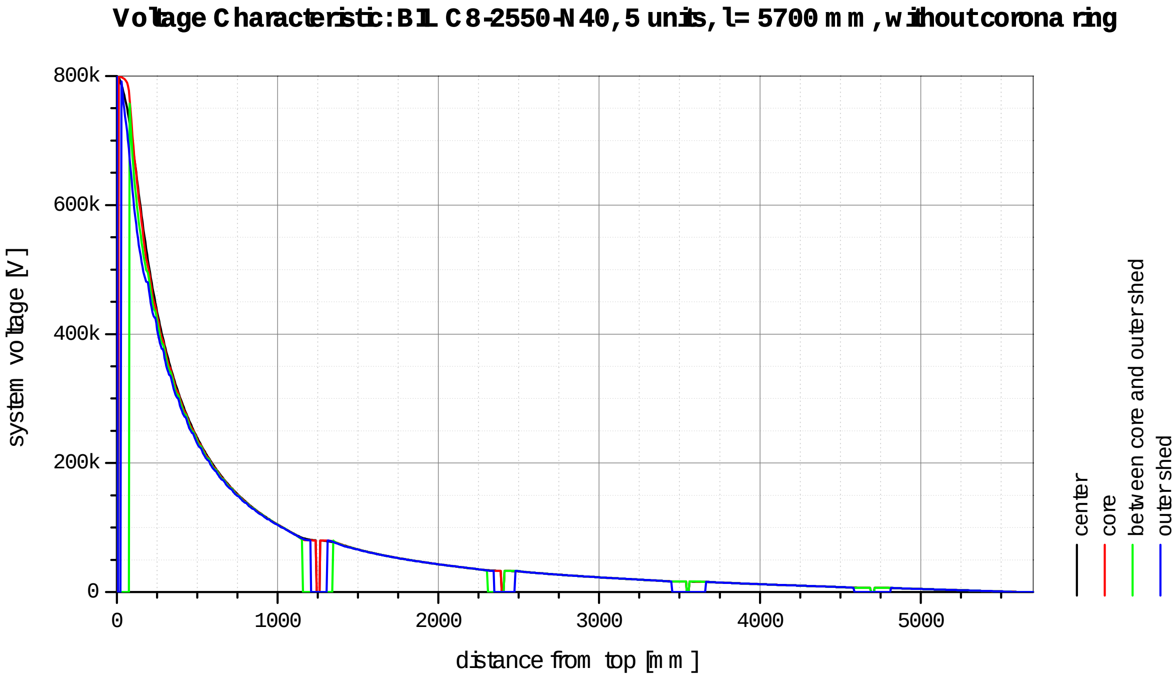


a) Course of the electric field along the whole insulator at different radial points

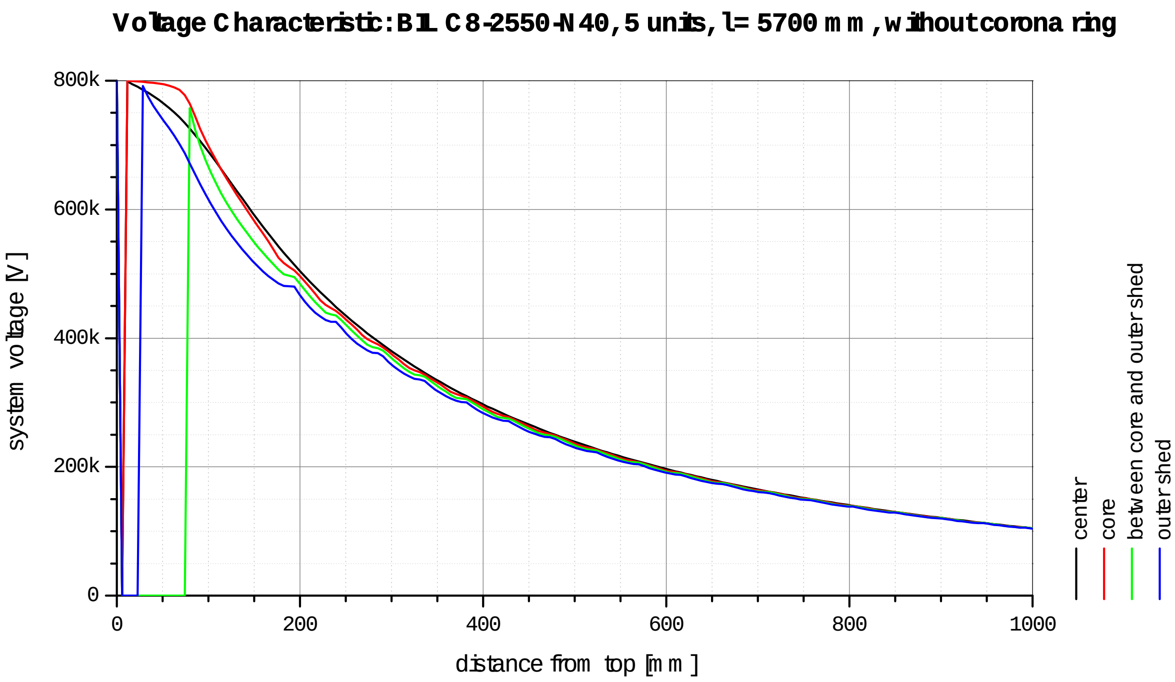


b) Course of the electric field along the first meter from the top at different radial points

Fig. 84: Field Distribution: BIL C8-2550-N40, 5 units, l = 5700 mm, without CR

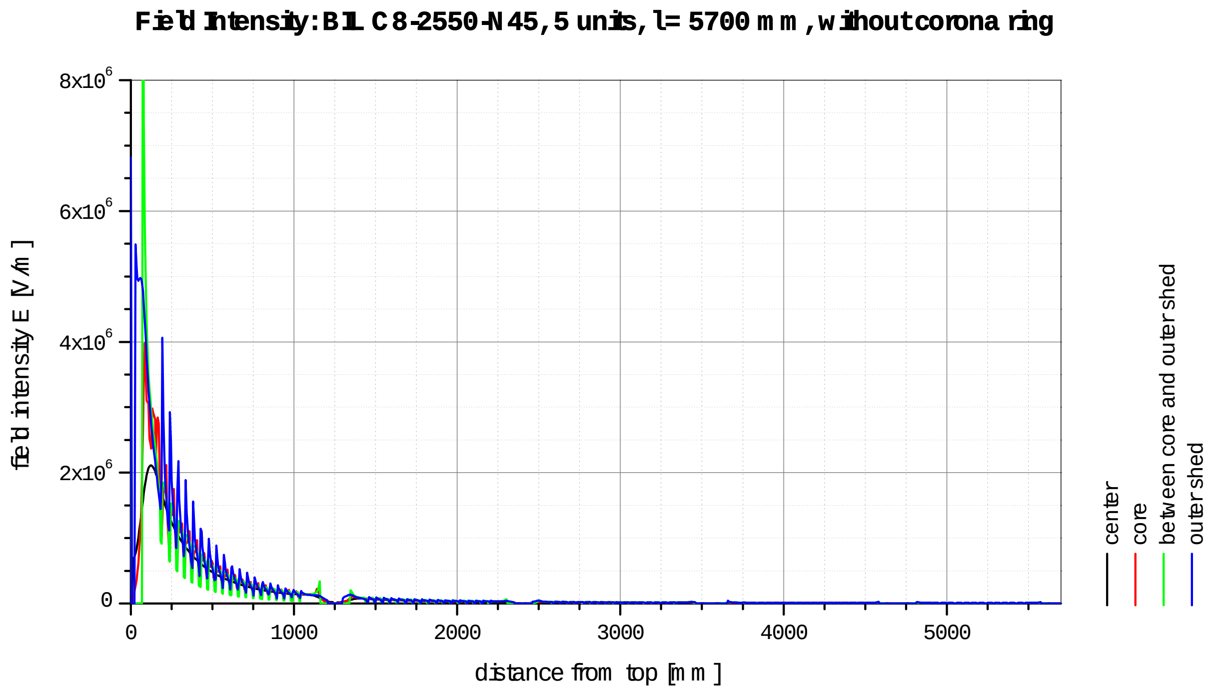


a) Voltage Characteristic along the whole insulator at different radial points

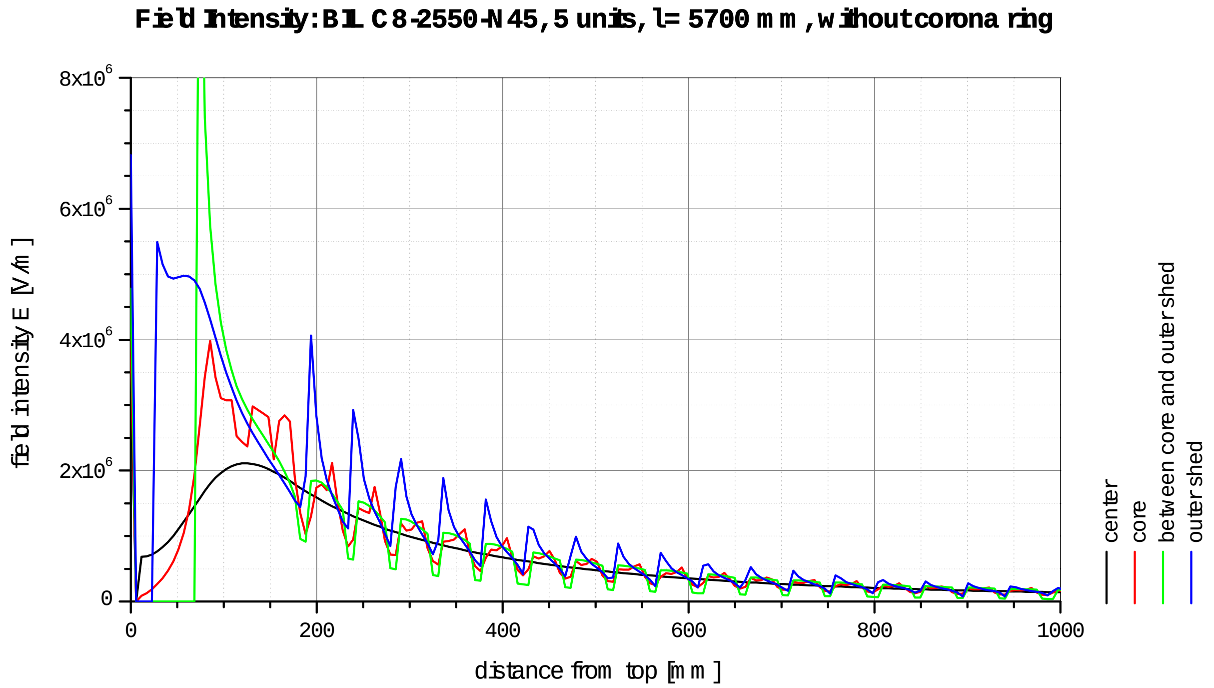


b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 85: Voltage Characteristic: BIL C8-2550-N40, 5 units, l = 5700 mm, without CR

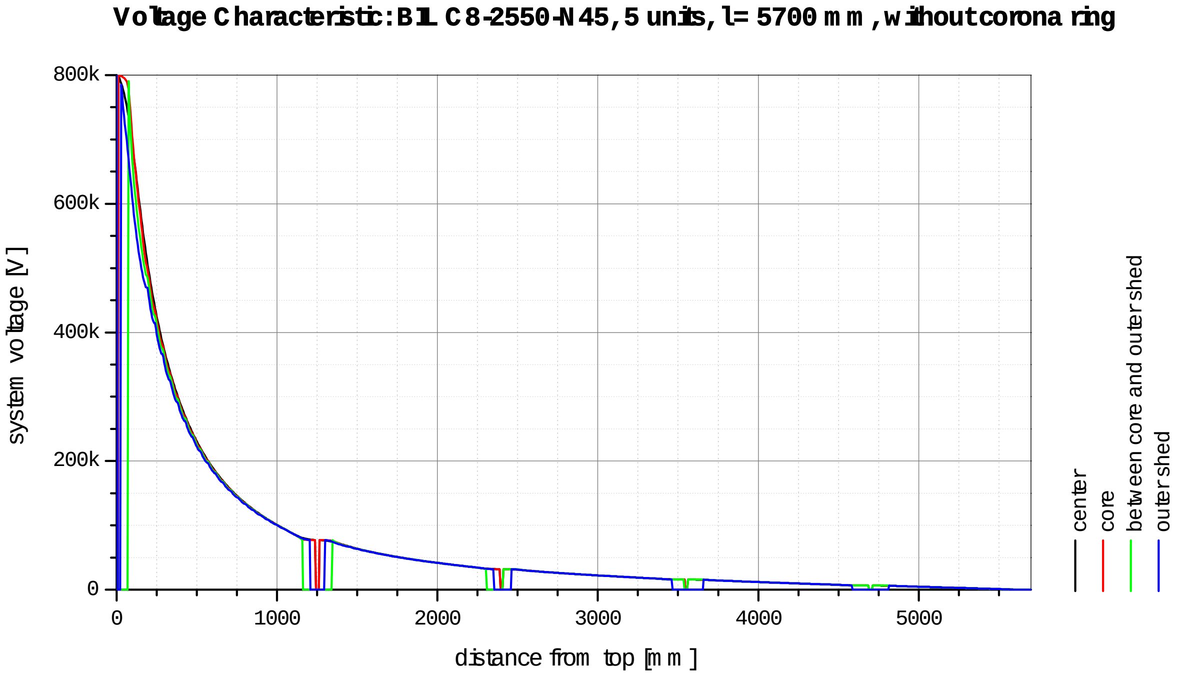


a) Course of the electric field along the whole insulator at different radial points

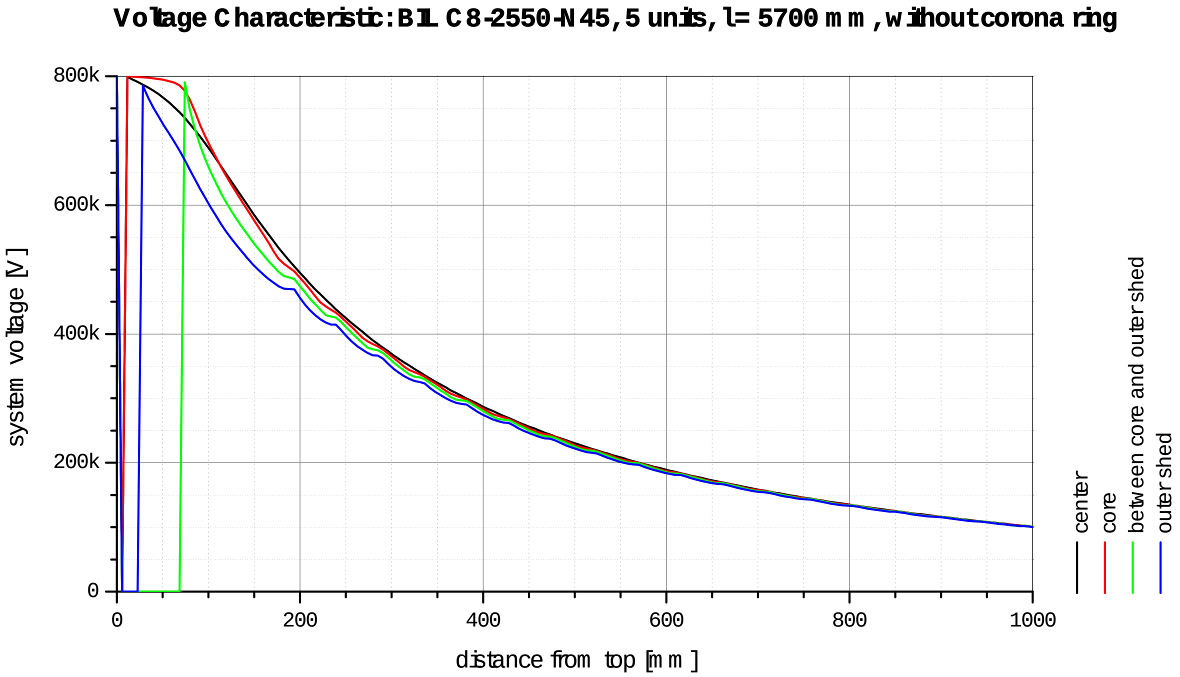


b) Course of the electric field along the first meter from the top at different radial points

Fig. 86: Field Distribution: BIL C8-2550-N45, 5 units, l = 5700 mm, without CR



a) Voltage Characteristic along the whole insulator at different radial points



b) Voltage Characteristic along the first meter from the top at different radial points

Fig. 87: Voltage Characteristic: BIL C8-2550-N45, 5 units, l = 5700 mm, without CR

A.7 ElecNet Script - Source Code

In the following unit the source code of the Microsoft Excel® marco used for remote controlling the field simulation software ElecNet is displayed.

```
'******************************** Variablendefinition *************************
'******************************** Variablendefinition *************************
Dim Elec As Object
Dim Doc As Object
Dim Con As Object
Dim Cur As Object
Dim Sol As Object
Dim Field As Object
Dim Fields As Object
Dim Mesh As Object
Dim Initial2dMesh As Object
Dim View As Object

Dim Visible As Boolean, Running As Boolean, check As Boolean
'model variables
Dim sv As Double, noi As Double, Airbox As Double ', g As Double
'shed input variables
Dim il As Double, ished As Double, oshed As Double, cored As Double, nis As Integer, nos As Integer, numins As Integer, drawins As
Integer
'spacing, overhang
Dim aone As Double, atwo As Double, tone As Double, ttwo As Double
'fitting
Dim bfrua As Double, bfh As Double, bft As Double, tfrua As Double, tfh As Double, tft As Double, fitrad As Double, fitthick As Double,
bfto As Double
'filling
Dim filthick As Double, filrad As Double
'angles
Dim alphao As Double, alphau As Double, sinso As Double, sinsu As Double, cosso As Double, cossu As Double, tanso As Double, tansu As
Double
'radial points
Dim sof As Double, irad As Double, orad As Double, core As Double, bfroi As Double, bcore As Double, tfroi As Double, tcore As Double
'core points
Dim ind As Double, sp As Double, ioffset As Double, ooffset As Double, tinsh As Double
'shed radius
Dim radau As Double, radob As Double, radun As Double
'shed points
Dim Pi1x As Double, Pi1y As Double, Pi2x As Double, Pi2y As Double, Pi23x As Double, Pi23y As Double, Pi3x As Double, Pi3y As Double
Dim Pi4x As Double, Pi4y As Double, Pi45x As Double, Pi45y As Double, Pi5x As Double, Pi5y As Double, Pi6x As Double, Pi6y As Double
Dim Pi67x As Double, Pi67y As Double, Pi7x As Double, Pi7y As Double, Pi8x As Double, Pi8y As Double
Dim Po1x As Double, Po1y As Double, Po2x As Double, Po2y As Double, Po23x As Double, Po23y As Double, Po3x As Double, Po3y As Double
Dim Po4x As Double, Po4y As Double, Po45x As Double, Po45y As Double, Po5x As Double, Po5y As Double, Po6x As Double, Po6y As Double
Dim Po67x As Double, Po67y As Double, Po7x As Double, Po7y As Double, Po8x As Double, Po8y As Double, versatz As Double
'corona variables
Dim cor_dia As Double, cor_x_offset As Double, cor_y_offset As Double, cor_true As Integer, total_height As Double
'helping variables
Dim a As Double, runs As Integer
'graph
Dim charge As Double, Max As Double, ID  As Double, FI As Double

Option Explicit

'******************************** StartElecNet ********************************
'******************************** StartElecNet ********************************
' Start ElecNet and set variables.
Public Sub StartElecNet()
    If Running Then
        Call MsgBox("ElecNet is already running.", vbOKOnly)
    Else
        Set Elec = CreateObject("Elecnet-TrialEdition.Application")
        Elec.Visible = Visible
        'Set Doc = Elec.newDocument
        'Set Con = Elec.GetConstants
        'Set Cur = Doc.getCurrentView
        'Set Sol = Doc.getSolution
        Running = True
    End If
End Sub

'******************************** CloseElecNet ***********************************
'******************************** CloseElecNet ***********************************
Public Sub CloseElecNet()
' Close MagNet and reset variables.
    If Not Running Then
        Call MsgBox("ElecNet is not running.", vbOKOnly)
    Else
        Call Cur.Close(Con.infoFalse)
        Call Elec.Exit
        Set Elec = Nothing
        Running = False
        Visible = False
    End If
```

```
End Sub

'******************************** Visibility **********************************
'******************************** Visibility **********************************
Public Sub Visibility()
'Toggle the MagNet visibility flag.
    If Not Running Then
        Call MsgBox("MagNet is not running.", vbOKOnly)
    Else
        If Visible Then
            Visible = (MsgBox("ElecNet is visible. Change to Invisible?", _
            vbYesNo) = vbNo)
            If Not Visible Then
                Elec.Visible = False
            End If
        Else
            Visible = (MsgBox("ElecNet is invisible. Change to visible?", _
            vbYesNo) = vbYes)
            If Visible Then
                Elec.Visible = True
            End If
        End If
    End If
End Sub

'******************************** RunModel ************************************
'******************************** RunModel ************************************
Public Sub RunModel()
    If Not Running Then
        Call MsgBox("MagNet is not running.", vbOKOnly)
    Else
        NewModel
        DrawInsulators
        MaterialProperties
        SetComponents
        MakeElektrodes

        cor_true = Tabelle1.Cells(6, 13)
        If cor_true = 1 Then
            Corona              'check if corona ring is enabled
        End If

        SetVoltage
        MakeAirbox
        SetBoundaryCondition
    End If
End Sub

'******************************** NewModel ************************************
'******************************** NewModel ************************************
Public Sub NewModel()
    'Call Cur.Close(Con.infoFalse)
    Set Doc = Elec.newDocument
    Set Sol = Doc.getSolution
    Set Con = Elec.GetConstants
    Set Cur = Doc.getCurrentView

    Call Doc.beginUndoGroup("Set Default Units", True)
    Call Doc.setDefaultLengthUnit("Millimeters")
    Call Doc.endUndoGroup
    Call Cur.setScaledToFit(True)
End Sub

'******************************** NewWorksheet ********************************
'******************************** NewWorksheet ********************************
Public Sub NewWorksheet()
    Call Cur.Close(Con.infoFalse)
    Call Elec.newDocument
End Sub

'******************************** Material properties *************************
'******************************** Material properties *************************
Public Sub MaterialProperties()
    check = Elec.getUserMaterialDatabase.isMaterialInDatabase("Ceramic")
    If check = True Then
        Call Elec.getUserMaterialDatabase.deleteMaterial("Ceramic")
    End If
    Call Elec.getUserMaterialDatabase.newMaterial("Ceramic")
    Call Elec.getUserMaterialDatabase.setMaterialColor("Ceramic", 128, 0, 0, 255)
    Call Elec.getUserMaterialDatabase.setMaterialCategories("Ceramic", Array())
    ReDim ArrayOfValues(0, 2)
```

```
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = 1
    ArrayOfValues(0, 2) = 0
    Call Elec.getUserMaterialDatabase.setMagneticPermeability("Ceramic", ArrayOfValues, Con.infoLinearIsotropicReal)
    ReDim ArrayOfValues(0, 1)
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = Tabelle1.Cells(29, 13)
    Call Elec.getUserMaterialDatabase.setElectricConductivity("Ceramic", ArrayOfValues, Con.infoLinearIsotropicReal)
    ReDim ArrayOfValues(0, 1)
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = Tabelle1.Cells(30, 13)
    Call Elec.getUserMaterialDatabase.setElectricPermittivity("Ceramic", ArrayOfValues, Con.infoLinearIsotropicReal)

    check = Elec.getUserMaterialDatabase.isMaterialInDatabase("Cement")
    If check = True Then
        Call Elec.getUserMaterialDatabase.deleteMaterial("Cement")
    End If
    Call Elec.getUserMaterialDatabase.newMaterial("Cement")
    Call Elec.getUserMaterialDatabase.setMaterialColor("Cement", 128, 128, 128, 255)
    Call Elec.getUserMaterialDatabase.setMaterialCategories("Cement", Array())
    ReDim ArrayOfValues(0, 2)
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = 1
    ArrayOfValues(0, 2) = 0
    Call Elec.getUserMaterialDatabase.setMagneticPermeability("Cement", ArrayOfValues, Con.infoLinearIsotropicReal)
    ReDim ArrayOfValues(0, 1)
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = Tabelle1.Cells(26, 13)
    Call Elec.getUserMaterialDatabase.setElectricConductivity("Cement", ArrayOfValues, Con.infoLinearIsotropicReal)
    ReDim ArrayOfValues(0, 1)
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = Tabelle1.Cells(27, 13)
    Call Elec.getUserMaterialDatabase.setElectricPermittivity("Cement", ArrayOfValues, Con.infoLinearIsotropicReal)

    check = Elec.getUserMaterialDatabase.isMaterialInDatabase("Silicon Rubber")
    If check = True Then
        Call Elec.getUserMaterialDatabase.deleteMaterial("Silicon Rubber")
    End If
    Call Elec.getUserMaterialDatabase.newMaterial("Silicon Rubber")
    Call Elec.getUserMaterialDatabase.setMaterialColor("Silicon Rubber", 128, 128, 0, 255)
    Call Elec.getUserMaterialDatabase.setMaterialCategories("Silicon Rubber", Array())
    ReDim ArrayOfValues(0, 2)
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = 1
    ArrayOfValues(0, 2) = 0
    Call Elec.getUserMaterialDatabase.setMagneticPermeability("Silicon Rubber", ArrayOfValues, Con.infoLinearIsotropicReal)
    ReDim ArrayOfValues(0, 1)
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = Tabelle1.Cells(23, 13)
    Call Elec.getUserMaterialDatabase.setElectricConductivity("Silicon Rubber", ArrayOfValues, Con.infoLinearIsotropicReal)
    ReDim ArrayOfValues(0, 1)
    ArrayOfValues(0, 0) = 20
    ArrayOfValues(0, 1) = Tabelle1.Cells(24, 13)
    Call Elec.getUserMaterialDatabase.setElectricPermittivity("Silicon Rubber", ArrayOfValues, Con.infoLinearIsotropicReal)
End Sub

'********************************* DrawInsulators ******************************
'********************************* DrawInsulators ******************************
Public Sub DrawInsulators()

    noi = Tabelle1.Cells(5, 13)                         'number of insulators

    For numins = 0 To noi - 1
        il = Tabelle1.Cells(5, 4 + numins)              'insulator length
        ished = Tabelle1.Cells(15, 4 + numins)         'inner shed diameter
        oshed = Tabelle1.Cells(10, 4 + numins)         'outer shed diameter
        cored = Tabelle1.Cells(8, 4 + numins)           'core diameter
        nis = Tabelle1.Cells(16, 4 + numins)            '# inner sheds
        nos = Tabelle1.Cells(11, 4 + numins)            '# outer sheds

        aone = Tabelle1.Cells(17, 4 + numins)           'A1 - overhang alternating sheds
        atwo = Tabelle1.Cells(12, 4 + numins)           'A2 - overhang normal sheds
        tone = Tabelle1.Cells(18, 4 + numins)           'T1 - spacing alternating sheds
        ttwo = Tabelle1.Cells(13, 4 + numins)           'T2 - spacing normal sheds

        bfrua = 0.5 * Tabelle1.Cells(20, 4 + numins)    'bottom fitting radius
        bfh = Tabelle1.Cells(21, 4 + numins)            'bottom fitting hight
        bft = Tabelle1.Cells(22, 4 + numins)            'bottom fitting thinkness

        tfrua = 0.5 * Tabelle1.Cells(24, 4 + numins)    'top fitting radius
        tfh = Tabelle1.Cells(25, 4 + numins)            'top fitting hight
```

```
tft = Tabelle1.Cells(26, 4 + numins)            'top fitting thinkness

radau = Tabelle1.Cells(28, 4 + numins)          'outher shed radius
radob = Tabelle1.Cells(29, 4 + numins)          'top shed radius
radun = Tabelle1.Cells(30, 4 + numins)          'bottom shed radius
sof = Tabelle1.Cells(41, 4 + numins)            'stapeloffset

alphao = Tabelle1.Cells(32, 4 + numins)         'top shed angle
alphau = Tabelle1.Cells(33, 4 + numins)         'bottom shed angle
sinso = Tabelle1.Cells(43, 4 + numins)          'sin top angle
cosso = Tabelle1.Cells(44, 4 + numins)          'cos top angle
sinsu = Tabelle1.Cells(45, 4 + numins)          'sin bottom angle
cossu = Tabelle1.Cells(46, 4 + numins)          'cos bottom angle

fitrad = 3                                      'small radius to remove the edges at the fittings
fitthick = 15                                   'thickness of the fitting
bfto = 10                                       'thickness of the bottom plate next to the insulation material
filthick = 4                                    'thickness of the filling
filrad = fitthick                               'radius of the filling at the top of the fitting

bfroi = 0.5 * Tabelle1.Cells(42, 4 + numins)    'inside bottom fitting radius
bcore = cored / 2                               'bottom porcelain bcore radius
tfroi = 0.5 * Tabelle1.Cells(42, 4 + numins)    'inside top fitting radius
tcore = cored / 2                               'top porcelain tcore radius
irad = ished / 2                               'alternating shed radius
orad = oshed / 2                               'normal shed radius
core = cored / 2                                'core radius

tanso = sinso / cosso
tansu = sinsu / cossu

versatz = Tabelle1.Cells(49, 4 + numins)        'offset if startpoint of bottom shed radius is lower then the lowest point of
the shed
ind = il - bfh - tfh                            'insulating distance
sp = (ind - (nos - 1) * ttwo - nis * tone) / 2 - radau - versatz  'start point of first shed
ioffset = sof + bfh + sp + ttwo - versatz

'bottom start point
Pi1x = core
Pi1y = ioffset
'lower point of the bottom arc
Pi2x = core
Pi2y = ioffset + radau - cossu * radau + tansu * (irad - core - radau - sinsu * radau - radun - sinsu * radun) - radun + versatz
'center of the bottom arc
Pi23x = core + radun
Pi23y = ioffset + radau - cossu * radau + tansu * (irad - core - radau - sinsu * radau - radun - sinsu * radun) - radun + versatz
'upper point of the bottom arc
Pi3x = core + radun + sinsu * radun
Pi3y = ioffset + radau - cossu * radau + tansu * (irad - core - radau - sinsu * radau - radun - sinsu * radun) + versatz
'lower point of the outher arc
Pi4x = irad - radau - sinsu * radau
Pi4y = ioffset + radau - cossu * radau + versatz
'center of the outher arc
Pi45x = irad - radau
Pi45y = ioffset + radau + versatz
'upper point of the outher arc
Pi5x = irad - radau + sinso * radau
Pi5y = ioffset + radau + cosso * radau + versatz
'Arc lower point of the top arc
Pi6x = core + radob - sinso * radob
Pi6y = ioffset + radau + cosso * radau + tanso * (irad - core - radob + sinso * radob - radau + sinso * radau) + versatz
'center of the top arc
Pi67x = core + radob
Pi67y = ioffset + radau + cosso * radau + tanso * (irad - core - radob + sinso * radob - radau + sinso * radau) + radob + versatz
'upper point of the top arc
Pi7x = core
Pi7y = ioffset + radau + cosso * radau + tanso * (irad - core - radob + sinso * radob - radau + sinso * radau) + radob + versatz
'top end point
Pi8x = core
Pi8y = ioffset + tone

ooffset = sof + bfh + sp
'bottom start point
Po1x = core
Po1y = ooffset
'lower point of the bottom arc
Po2x = core
Po2y = ooffset + radau - cossu * radau + tansu * (orad - core - radau - sinsu * radau - radun - sinsu * radun) - radun + versatz
'center of the bottom arc
Po23x = core + radun
Po23y = ooffset + radau - cossu * radau + tansu * (orad - core - radau - sinsu * radau - radun - sinsu * radun) - radun + versatz
```

```
'lower point of the outher arc
Po3x = core + radun + sinsu * radun
Po3y = ooffset + radau - cossu * radau + tansu * (orad - core - radau - sinsu * radau - radun - sinsu * radun) + versatz
'lower point of the outher arc
Po4x = orad - radau - sinsu * radau
Po4y = ooffset + radau - cossu * radau + versatz
'center of the outher arc
Po45x = orad - radau
Po45y = ooffset + radau + versatz
'upper point of the outher arc
Po5x = orad - radau + sinso * radau
Po5y = ooffset + radau + cosso * radau + versatz
'Arc lower point of the top arc
Po6x = core + radob - sinso * radob
Po6y = ooffset + radau + cosso * radau + tanso * (orad - core - radob + sinso * radob - radau + sinso * radau) + versatz
'center of the top arc
Po67x = core + radob
Po67y = ooffset + radau + cosso * radau + tanso * (orad - core - radob + sinso * radob - radau + sinso * radau) + radob + versatz
'upper point of the top arc
Po7x = core
Po7y = ooffset + radau + cosso * radau + tanso * (orad - core - radob + sinso * radob - radau + sinso * radau) + radob + versatz
'top end point
Po8x = core
Po8y = ooffset + ttwo

'**************************** fitting ***********************************
'**************************** fitting ***********************************

'**************************** bottom fitting ****************************
If numins = 0 Then
    Call Cur.newline(0, sof + 0, bfrua, sof + 0)
End If

Call Cur.newline(bfrua, sof + 0, bfrua, sof + bft - fitrad)   'Linie senkrecht Außenradius
Call Cur.newarc(bfrua - fitrad, sof + bft - fitrad, bfrua, sof + bft - fitrad, bfrua - fitrad, sof + bft) 'Radius unten

Call Cur.newarc(bfrua * bfrua / bfh * 1.5, sof + bfh * bfh / bfrua * 1.5, 0.5 * (bfrua - bfroi) + bfroi, sof + 0.5 * bfh, bfrua
- fitrad, sof + bft) 'schräge
Call Cur.newline(bfroi + fitthick, sof + bfh - fitrad, 0.5 * (bfrua - bfroi) + bfroi, sof + 0.5 * bfh) 'schräg oben

Call Cur.newarc(bfroi + fitthick - fitrad, sof + bfh - fitrad, bfroi + fitthick, sof + bfh - fitrad, bfroi + fitthick - fitrad,
sof + bfh)     'Radius oben
Call Cur.newline(bfroi + fitthick - fitrad, sof + bfh, bfroi + 1, sof + bfh)   'Linie oben waagrecht
Call Cur.newarc(bfroi + 1, sof + bfh - 1, bfroi + 1, sof + bfh, bfroi, sof + bfh - 1)
Call Cur.newline(bfroi, sof + bfh - 1, bfroi, sof + bfto + 1)  'Linie innen senkrecht
Call Cur.newarc(bfroi - 1, sof + bfto + 1, bfroi - 1, sof + bfto, bfroi, sof + bfto + 1)
Call Cur.newline(bfroi - 1, sof + bfto, 0, sof + bfto)       'Linie innen waagrecht
Call Cur.newline(0, sof + bfto, 0, sof + 0)         'Linie Kern senkrecht

'**************************** top fitting *******************************
If numins = noi - 1 Then
        Call Cur.newline(0, sof + 0 + il, tfrua - fitrad, sof + 0 + il)
        Call Cur.newarc(tfrua - fitrad, sof + il - fitrad, tfrua, sof + il - fitrad, tfrua - fitrad, sof + il)
End If
If numins < noi - 1 Then
    Call Cur.newline(tfrua, sof + 0 + il - fitrad, tfrua, sof + 0 + il)
End If

Call Cur.newline(tfrua, sof + 0 + il - fitrad, tfrua, sof - tft + fitrad + il)
Call Cur.newarc(tfrua - fitrad, sof - tft + fitrad + il, tfrua - fitrad, sof - tft + il, tfrua, sof - tft + fitrad + il)

Call Cur.newarc(tfrua / tfh * tfrua * 1.5, sof + il - tfh * tfh / tfrua * 1.5, tfrua - fitrad, sof - tft + il, 0.5 * (tfrua -
tfroi) + tfroi, sof - 0.5 * tfh + il)
Call Cur.newline(tfroi + fitthick, sof - tfh + fitrad + il, 0.5 * (tfrua - tfroi) + tfroi, sof - 0.5 * tfh + il)   'schräg unten

Call Cur.newarc(tfroi + fitthick - fitrad, sof + il - tfh + fitrad, tfroi + fitthick - fitrad, sof - tfh + il, tfroi + fitthick,
 sof - tfh + fitrad + il)
Call Cur.newline(tfroi + 1, sof - tfh + il, tfroi + fitthick - fitrad, sof - tfh + il)
Call Cur.newarc(tfroi + 1, sof + il - tfh + 1, tfroi, sof + il - tfh + 1, tfroi + 1, sof + il - tfh)
Call Cur.newline(tfroi, sof - bfto - 1 + il, tfroi, sof - tfh + 1 + il)
Call Cur.newarc(tfroi - 1, sof + il - bfto - 1, tfroi, sof + il - bfto - 1, tfroi - 1, sof + il - bfto)
Call Cur.newline(0, sof - bfto + il, tfroi - 1, sof - bfto + il)
Call Cur.newline(0, sof - bfto + il, 0, sof + 0 + il)


'**************************** filling ***********************************
'**************************** filling ***********************************

'**************************** bottom cement *****************************
Call Cur.newline(bcore, sof + bfh, bcore, sof + bfto + 10) 'innen senkrecht
Call Cur.newline(bcore, sof + bfto + 10, bcore - 5, sof + bfto)
```

```
        Call Cur.newarc(bfroi + filrad, sof + bfh + filrad, bcore, sof + bfh + filrad, bcore + filrad, sof + bfh)

        '**************************** top cement ********************************
        Call Cur.newarc(tcore + filrad, sof + il - tfh - filrad, tcore + filrad, sof + il - tfh, tcore, sof + il - tfh - filrad)
        Call Cur.newline(tcore, sof - bfto - 10 + il, tcore, sof - tfh + il)
        Call Cur.newline(tcore - 5, sof + il - bfto, tcore, sof + il - bfto - 10)


        '**************************** sheds *************************************
        '**************************** sheds *************************************

        '**************************** other sheds *******************************
        For runs = 0 To nos - 1
            a = tone + ttwo
            a = a * (runs)
            Call Cur.newline(Po1x, Po1y + a, Po2x, Po2y + a)
            Call Cur.newline(Po3x, Po3y + a, Po4x, Po4y + a)
            Call Cur.newline(Po5x, Po5y + a, Po6x, Po6y + a)
            Call Cur.newline(Po7x, Po7y + a, Po8x, Po8y + a)
            Call Cur.newarc(Po23x, Po23y + a, Po3x, Po3y + a, Po2x, Po2y + a)
            Call Cur.newarc(Po45x, Po45y + a, Po4x, Po4y + a, Po5x, Po5y + a)
            Call Cur.newarc(Po67x, Po67y + a, Po7x, Po7y + a, Po6x, Po6y + a)
        Next

        '**************************** core **************************************
        Call Cur.newline(0, sof + bfto, 0, sof + il - bfto) 'center
        Call Cur.newline(bcore, sof + bfh, bcore, sof + bfh + sp)   'core bottom
        Call Cur.newline(tcore, sof + il - tfh, tcore, Po8y + a)    'core top

        '**************************** inner sheds *******************************
        For runs = 0 To nis - 1
            a = tone + ttwo
            a = a * (runs)
            Call Cur.newline(Pi1x, Pi1y + a, Pi2x, Pi2y + a)
            Call Cur.newline(Pi3x, Pi3y + a, Pi4x, Pi4y + a)
            Call Cur.newline(Pi5x, Pi5y + a, Pi6x, Pi6y + a)
            Call Cur.newline(Pi7x, Pi7y + a, Pi8x, Pi8y + a)
            Call Cur.newarc(Pi23x, Pi23y + a, Pi3x, Pi3y + a, Pi2x, Pi2y + a)
            Call Cur.newarc(Pi45x, Pi45y + a, Pi4x, Pi4y + a, Pi5x, Pi5y + a)
            Call Cur.newarc(Pi67x, Pi67y + a, Pi7x, Pi7y + a, Pi6x, Pi6y + a)
        Next
    Next
End Sub

'********************************* SetComponents *******************************
'********************************* SetComponents *******************************
Public Sub SetComponents()
    noi = Tabelle1.Cells(5, 13)          'number of insulators

    Call Cur.unselectAll
    For numins = 0 To noi - 1                               'top filling
        bcore = 0.5 * Tabelle1.Cells(8, 4 + numins)         'bottom porcelain bcore radius
        sof = Tabelle1.Cells(41, 4 + numins)                'stapeloffset
        il = Tabelle1.Cells(5, 4 + numins)                  'insulator length
        tfh = Tabelle1.Cells(25, 4 + numins)                'top fitting hight
        Call Cur.selectAt(bcore + 0.5, sof + il - tfh / 2, Con.infoSetSelection, Array(Con.infoSliceSurface))
        ReDim ArrayOfValues(0)
        ArrayOfValues(0) = "Filling top " & numins + 1
        Call Cur.makeComponentInAnArc(0, 0, 0, -1, Tabelle1.Cells(20, 13), ArrayOfValues, "Name=Cement",
        Con.infoMakeComponentUnionSurfaces Or Con.infoMakeComponentRemoveVertices)
    Next

    Call Cur.unselectAll
    For numins = 0 To noi - 1                               'bottom filling
        bcore = 0.5 * Tabelle1.Cells(8, 4 + numins)         'bottom porcelain bcore radius
        sof = Tabelle1.Cells(41, 4 + numins)                'stapeloffset
        bfh = Tabelle1.Cells(21, 4 + numins)                'bottom fitting hight
        Call Cur.selectAt(bcore + 0.5, sof + bfh / 2, Con.infoSetSelection, Array(Con.infoSliceSurface))
        ReDim ArrayOfValues(0)
        ArrayOfValues(0) = "Filling bottom " & numins + 1
        Call Cur.makeComponentInAnArc(0, 0, 0, -1, Tabelle1.Cells(20, 13), ArrayOfValues, "Name=Cement",
        Con.infoMakeComponentUnionSurfaces Or Con.infoMakeComponentRemoveVertices)
    Next

    Call Cur.unselectAll
    For numins = 0 To noi - 1                               'ceramic core
        cored = Tabelle1.Cells(8, 4 + numins)               'core diameter
        bcore = cored / 2                                   'bottom porcelain bcore radius
        sof = Tabelle1.Cells(41, 4 + numins)                'stapeloffset
        il = Tabelle1.Cells(5, 4 + numins)                  'insulator length
        Call Cur.selectAt(bcore / 2, sof + il / 2, Con.infoSetSelection, Array(Con.infoSliceSurface))
```

```
        ReDim ArrayOfValues(0)
        ArrayOfValues(0) = "Core " & numins + 1
        Call Cur.makeComponentInAnArc(0, 0, 0, -1, Tabelle1.Cells(20, 13), ArrayOfValues, "Name=Ceramic",
        Con.infoMakeComponentUnionSurfaces Or Con.infoMakeComponentRemoveVertices)
    Next

    Call Cur.unselectAll
    For numins = 0 To 0                                 'first bottom aluminium fitting
        bfrua = 0.5 * Tabelle1.Cells(20, 4 + numins)    'bottom fitting radius unten außen
        sof = Tabelle1.Cells(41, 4 + numins)            'stapeloffset
        Call Cur.selectAt(bfrua / 2, sof + 1, Con.infoSetSelection, Array(Con.infoSliceSurface))
        ReDim ArrayOfValues(0)
        ArrayOfValues(0) = "Fitting " & numins + 1
        Call Cur.makeComponentInAnArc(0, 0, 0, -1, Tabelle1.Cells(20, 13), ArrayOfValues, "Name=Aluminum: 3.8e7 Siemens/meter",
        Con.infoMakeComponentUnionSurfaces Or Con.infoMakeComponentRemoveVertices)
    Next

    Call Cur.unselectAll
    For numins = 0 To noi - 1                           'combined bottom and top aluminium fitting
        sof = Tabelle1.Cells(41, 4 + numins)            'stapeloffset
        il = Tabelle1.Cells(5, 4 + numins)              'insulator length
        tfrua = 0.5 * Tabelle1.Cells(24, 4 + numins)    'top fitting radius unten außen
        Call Cur.selectAt(tfrua / 2, sof + il, Con.infoSetSelection, Array(Con.infoSliceSurface))
        ReDim ArrayOfValues(0)
        ArrayOfValues(0) = "Fitting " & numins + 2
        Call Cur.makeComponentInAnArc(0, 0, 0, -1, Tabelle1.Cells(20, 13), ArrayOfValues, "Name=Aluminum: 3.8e7 Siemens/meter",
        Con.infoMakeComponentUnionSurfaces Or Con.infoMakeComponentRemoveVertices)
    Next

Call Cur.SelectAll(Con.infoSetSelection, Array(Con.infoSliceLine, Con.infoSliceArc))
Call Cur.deleteSelection
End Sub

'********************************* MakeElektrodes ******************************
'********************************* MakeElektrodes ******************************
Public Sub MakeElektrodes()
    noi = Tabelle1.Cells(5, 13)          'number of insulators

    Call Cur.unselectAll
    Call Cur.selectObject("Fitting " & 1, Con.infoSetSelection)
    ReDim ArrayOfValues(0)
    ArrayOfValues(0) = "Fitting " & 1
    Call Doc.makeElectrode(ArrayOfValues)           'first and lowest electrode

    If noi > 1 Then
        For a = 1 To noi - 1
            Call Cur.unselectAll
            Call Cur.selectObject("Fitting " & a + 1, Con.infoToggleInSelection)
            ReDim ArrayOfValues(0)
            ArrayOfValues(0) = "Fitting " & a + 1
            Call Doc.makeElectrode(ArrayOfValues)   'all electrodes inbetween the lowest and highest electrode
        Next
    End If

    Call Cur.selectObject("Fitting " & noi + 1, Con.infoSetSelection)
    ReDim ArrayOfValues(0)
    ArrayOfValues(0) = "Fitting " & noi + 1
    Call Doc.makeElectrode(ArrayOfValues)           'last and highest electrode
End Sub

'*************************************Corona Ring *****************************
'*************************************Corona Ring *****************************
Public Sub Corona()
    total_height = Tabelle1.Cells(4, 17)                                        'total insulator height
    cor_dia = Tabelle1.Cells(34, 13)                                            'electrode diameter
    cor_x_offset = 0.5 * Tabelle1.Cells(33, 13) - 0.5 * cor_dia                 'corona ring diameter
    cor_y_offset = total_height - Tabelle1.Cells(35, 13) + 0.5 * cor_dia        'y-offset
    sv = Tabelle1.Cells(4, 13)                                                  'systemvoltage in Volt

    Call Cur.newcircle(cor_x_offset, cor_y_offset, 0.5 * cor_dia)
    Call Cur.selectAt(cor_x_offset, cor_y_offset, Con.infoSetSelection, Array(Con.infoSliceSurface))
    ReDim ArrayOfValues(0)
    ArrayOfValues(0) = "Corona Ring"
    Call Cur.makeComponentInAnArc(0, 0, 0, -1, 90, ArrayOfValues, "Name=Aluminum: 3.8e7 Siemens/meter",
    Con.infoMakeComponentUnionSurfaces Or Con.infoMakeComponentRemoveVertices)

    Call Cur.selectObject("Corona Ring", Con.infoSetSelection)
    ReDim ArrayOfValues(0)
    ArrayOfValues(0) = "Corona Ring"
    Call Doc.makeElectrode(ArrayOfValues)
End Sub
```

```
'********************************* SetVoltage ***********************************
'********************************* SetVoltage ***********************************
Public Sub SetVoltage()
    sv = Tabelle1.Cells(4, 13)            'systemvoltage in Volt

    Call Doc.setElectrodeVoltage("Electrode#1", 0, 0)

    If noi > 1 Then
        For a = 1 To noi - 1
            Call Cur.selectObject("Electrode#" & 1 + a, Con.infoSetSelection)
            Call Doc.beginUndoGroup("Set Properties", True)
            Call Doc.setFloatingElectrode("Electrode#" & 1 + a)
            Call Doc.endUndoGroup
        Next
    End If

    Call Cur.selectObject("Electrode#" & noi + 1, Con.infoSetSelection)
    Call Doc.beginUndoGroup("Set Properties", True)
    Call Doc.setElectrodeVoltage("Electrode#" & noi + 1, sv, 0)
    Call Doc.endUndoGroup

    cor_true = Tabelle1.Cells(6, 13)
    If cor_true = 1 Then             'check if corana ring is enabled
        Call Doc.setElectrodeVoltage("Electrode#" & noi + 2, sv, 0)
    End If
End Sub

'********************************* MakeAirbox ***********************************
'********************************* MakeAirbox ***********************************
Public Sub MakeAirbox()
    Airbox = Tabelle1.Cells(10, 13)        'airbox size - 4 times the insulator height

    Call Cur.newline(0, 0, 0, Airbox)
    Call Cur.newline(0, Airbox, Airbox, Airbox)
    Call Cur.newline(Airbox, Airbox, Airbox, 0)
    Call Cur.newline(Airbox, 0, 0, 0)

    Call Cur.selectAt(Airbox / 2, Airbox / 2, Con.infoSetSelection, Array(Con.infoSliceSurface))
    ReDim ArrayOfValues(0)
    ArrayOfValues(0) = "Air Box"
    Call Cur.makeComponentInAnArc(0, 0, 0, -1, Tabelle1.Cells(20, 13), ArrayOfValues, "Name=AIR", Con.infoMakeComponentUnionSurfaces Or
    Con.infoMakeComponentIgnoreHoles Or Con.infoMakeComponentRemoveVertices)
End Sub

'********************************* SetBoundaryCondition ************************
'********************************* SetBoundaryCondition ************************
Public Sub SetBoundaryCondition()
    Call Doc.beginUndoGroup("Assign Boundary Condition")
    ReDim ArrayOfValues(0)
    ArrayOfValues(0) = "Air Box,Face#3"
    Call Doc.createBoundaryCondition(ArrayOfValues, "BoundaryCondition#1")
    Call Doc.setGround("BoundaryCondition#1")
End Sub

'********************************* Solve ****************************************
'********************************* Solve ****************************************
Public Sub Solve()
    '************** Solver Options *****************
    Call Doc.beginUndoGroup("Set Solver Options", True)
    Call Doc.setSolverMaterialType(Con.infoLinearMaterial)
    Call Doc.setMaxNumberOfNewtonIterations(Tabelle1.Cells(11, 13))
    Call Doc.setNewtonTolerance(Tabelle1.Cells(12, 13))
    Call Doc.setPolynomialOrder("", Tabelle1.Cells(13, 13))
    Call Doc.setImproveMeshQuality(True)
    Call Doc.endUndoGroup
    Call Doc.setCGTolerance(Tabelle1.Cells(14, 13))
    Call Doc.setSourceFrequency(Tabelle1.Cells(15, 13))
    Call Doc.endUndoGroup
    Call Doc.beginUndoGroup("Set Adaption Options", True)
    Call Doc.useHAdaption(True)
    Call Doc.setHAdaptionRefinement(Tabelle1.Cells(16, 13))
    Call Doc.setAdaptionTolerance(Tabelle1.Cells(17, 13))
    Call Doc.setMaximumNumberOfAdaptionSteps(Tabelle1.Cells(18, 13))
    Call Doc.setCurvatureRefinementMinimumElementSize("", Tabelle1.Cells(19, 13))

    'ReDim Time(0)
    'ReDim temperature(0)
    'ReDim convection(0)
    'ReDim radiation(0)
    'Time(0) = 0
```

```
    'temperature(0) = 20
    'convection(0) = 5.5
    'radiation(0) = 0
    'Call Doc.setEnvironment("BoundaryCondition#1", Time, temperature, convection, radiation)

    Dim StoredEnergy As Double
    If (Doc.isValidForStatic2dSolver) Then
        Doc.solveStatic2d
        Call Cur.viewStaticFields(1, "V", "V", "None")   '(contour, shaded, arrow)
    End If
End Sub

'******************************** FieldLineGraph ******************************
'******************************** FieldLineGraph ******************************

Public Sub Detail1()    'V total view
    tinsh = Tabelle1.Cells(4, 17)
    ID = Cur.getId()
    Set View = Doc.getView(ID)
    Call Cur.viewStaticFields(1, "V", "V", "None")
    Call Doc.beginUndoGroup("Set Shaded Plot Properties", True)
    Call View.getOverlay("Shaded Plot").setNumberOfValues(41)
    Call View.getOverlay("Shaded Plot").SetRange(0, sv)
    Call Doc.endUndoGroup
    Call Doc.beginUndoGroup("Set Contour Plot Properties", True)
    Call View.getOverlay("Contour Plot").setNumberOfValues(41)
    Call View.getOverlay("Contour Plot").SetRange(0, sv)
    Call Doc.endUndoGroup
    Call View.Zoom(-300, tinsh + 300, tinsh + 300, -300)
End Sub

Public Sub Detail2()    'V detail
    tinsh = Tabelle1.Cells(4, 17)
    ID = Cur.getId()
    Set View = Doc.getView(ID)
    Call Cur.viewStaticFields(1, "V", "V", "None")
    Call Doc.beginUndoGroup("Set Shaded Plot Properties", True)
    Call View.getOverlay("Shaded Plot").setNumberOfValues(41)
    Call View.getOverlay("Shaded Plot").SetRange(0, sv)
    Call Doc.endUndoGroup
    Call Doc.beginUndoGroup("Set Contour Plot Properties", True)
    Call View.getOverlay("Contour Plot").setNumberOfValues(41)
    Call View.getOverlay("Contour Plot").SetRange(0, sv)
    Call Doc.endUndoGroup
    Call View.Zoom(-50, tinsh, 600, tinsh - 300)
End Sub

Public Sub Detail3()    'E total view
    tinsh = Tabelle1.Cells(4, 17)
    ID = Cur.getId()
    Set View = Doc.getView(ID)
    Call Cur.viewStaticFields(1, "|E| smoothed", "|E| smoothed", "None")
    Call Doc.beginUndoGroup("Set Shaded Plot Properties", True)
    Call View.getOverlay("Shaded Plot").setNumberOfValues(41)
    Call View.getOverlay("Shaded Plot").SetRange(0, sv)
    Call Doc.endUndoGroup
    Call Doc.beginUndoGroup("Set Contour Plot Properties", True)
    Call View.getOverlay("Contour Plot").setNumberOfValues(41)
    Call View.getOverlay("Contour Plot").SetRange(0, sv)
    Call Doc.endUndoGroup
    Call View.Zoom(-300, tinsh + 300, tinsh + 300, -300)
End Sub

Public Sub Detail4() 'E detail
    tinsh = Tabelle1.Cells(4, 17)
    FI = Tabelle1.Cells(21, 13)
    ID = Cur.getId()
    Set View = Doc.getView(ID)
    Call Cur.viewStaticFields(1, "|E| smoothed", "|E| smoothed", "None")
    Call Doc.beginUndoGroup("Set Shaded Plot Properties", True)
    Call View.getOverlay("Shaded Plot").setNumberOfValues(41)
    Call View.getOverlay("Shaded Plot").SetRange(0, FI)
    Call Doc.endUndoGroup
    Call Doc.beginUndoGroup("Set Contour Plot Properties", True)
    Call View.getOverlay("Contour Plot").setNumberOfValues(41)
    Call View.getOverlay("Contour Plot").SetRange(0, FI)
    Call Doc.endUndoGroup
    Call View.Zoom(-50, tinsh, 600, tinsh - 300)
End Sub

Public Sub Detail5() 'hybrid detail
```

```
    tinsh = Tabelle1.Cells(4, 17)
    FI = Tabelle1.Cells(21, 13)
    ID = Cur.getId()
    Set View = Doc.getView(ID)
    Call Cur.viewStaticFields(1, "V", "|E| smoothed", "None")
    Call Doc.beginUndoGroup("Set Shaded Plot Properties", True)
    Call View.getOverlay("Shaded Plot").setNumberOfValues(41)
    Call View.getOverlay("Shaded Plot").SetRange(0, 4000000)
    Call Doc.endUndoGroup
    Call Doc.beginUndoGroup("Set Contour Plot Properties", True)
    Call View.getOverlay("Contour Plot").setNumberOfValues(41)
    Call View.getOverlay("Contour Plot").SetRange(0, sv)
    Call Doc.endUndoGroup
    Call View.Zoom(-50, tinsh, 600, tinsh - 300)
End Sub

Public Sub FieldLineGraph()
    'Set Fields = View.getFields(Con.infoShadedPlot)
    'Call Doc.copyFieldToFieldPage(Field)
    'Set Mesh = Sol.getMesh(ArrayOfValues)
    'ReDim ArrayOfValues(1, 0)
    'Call Field.magnitude
    'Set Field = Sol.getUserField(Mesh, "My Field", Con.infoScalarField, 1, 1)
    'Set Field = Sol.getSystemField(Mesh, "|E| smoothed")
    'Set Field = Sol.getSystemField(Mesh, "V", Con.infoScalarField, 1, 1)

    'If (Field.getScalarFieldAtPoint(100, 100, 0, charge)) Then
    'Tabelle3.Cells(3, 2) = "True"
    'Else
    'Tabelle3.Cells(3, 2) = "false"
    'End If

    'Call Field.getScalarFieldAtPoint(100, 100, 0, charge)
    'Call Cur.viewStaticFields(1, "V")

    'Set Mesh = Sol.getMesh(ID, Con.infoZoneAllElements)
    'Set Initial2dMesh = Doc.getProblem(1).getInitialMesh(2)
    'Set Field = Sol.getSystemField(Initial2dMesh, "V")

    'Set Field = Sol.getStaticField(1, "|E|")
    'If (Field.isScalar()) Then
    'Tabelle3.Cells(1, 2) = "True"
    'Else
    '    Tabelle3.Cells(1, 2) = "false"
    'End If
    'charge = 0

    'Max = Field.getMax()
    'Tabelle3.Cells(4, 2) = Max

    'ReDim ArrayOfValues(0, 0)
    'Call Field.getFieldAtPoint(100, 100, 0, ArrayOfValues)
    'If (Field.getFieldAtPoint(100, 100, 0, ArrayOfValues)) Then
    'Tabelle3.Cells(2, 2) = "True"
    'Else
    'Tabelle3.Cells(2, 2) = "false"
    'End If

    'charge = Sol.getChargeOnElectrode(1, "Electrode#2")
    'Tabelle3.Cells(5, 2) = charge
    'Tabelle3.Cells(12, 2) = Doc.getNumberOfElectrodes

End Sub
```