Optimization of Capacitive and Resistive Field Grading Devices for Cable Joint and Termination

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Abstract — Grading the electric field in the reinforced insulation of cable joint and termination is one of the key problem in building reliable high voltage cable power lines.

There a two basic ways to solve this problem. In high voltage system mostly capacitive grading is used, which employs specially profiled stress-cone of a two-component rubber. Jojnts and terminations for low to medium voltage commonly employs resistive field grading using the cylindrical grading element with relatively high, often field-dependent conductivity.

In this paper we discuss the optimization of both stress-cone and resistive grader by means of FEA modelling of electric field. We also discuss which dielectric properties should have the resistive field grader for using with cable joints of higher voltage.

Keywords—Cable joint, cable termination, stress cone, field grading, capacitive field grading, impedance field grading, finite element analysis

I. Introduction.

The known equivalent circuit of the cable ending [1], [2], [3] is a RC network with longitudinal and transverse parallel RC elements. The RC network contains two lateral elements per cell. One of the RC filters represents the impedance between the conductor and the shield, whereas another RC filter represents the impedance of the reinforcing insulation of the cable joint between the conductor and the ground. The difference between these capacitive currents is the reason of non-uniform electric field distribution.

One way of grading the electric field along the cable end is modifying the longitudinal conductivity. That is known as an *impedance method* of the field grading. It is implemented by applying one or more semi-conductive coating layer over the cable insulation.

Another option is increasing of the capacity C_0 [3] of the reinforcing insulation to the ground. The grading effect of this capacity appears in conjunction with the conductive and semi-conductive shields, including the reflector of a stress cone. The curvature of the reflector should provide compensation of capacitive current by the displacement current through the reinforced insulation. This is the essence of the *geometric method*.

The *refraction method* involves increasing of the C_0 capacity by means of greatly increased permittivity of the main body of stress cone. To achieve this goal the stress cone is made from silicone rubber with a special filler, which increases the permittivity up to 10 times more than the XPLE insulation. However, the field grading effect of refraction method heavily depend on the harmonic spectrum of the cable voltage.

II. Capacitive Method of Electric Field Grading.

A. Definition

The capacitive field grading method is a combination of geometric and refractive methods [4], [5]. It provides reducing of the tangential electric field in the cable end, where the factory sheath, shield, and the polymer semi-conductive coatings are removed. This approach do not involve complex technological procedures of formation of the special properties of materials.

For example, the main module – the stress cone - can be made as a double-layered conical body (Fig. 1). The outer part – the main insulation body - is made from the rubber with good insulating properties, whereas the inner part - a reflector – is made from a molded rubber with simple conductive fillers (i.e. fine soot, metal dust). The reflector provides grading of the electric field in reinforced insulation. The space between the stress cone and the outer insulating sleeve is filled with liquid dielectric.

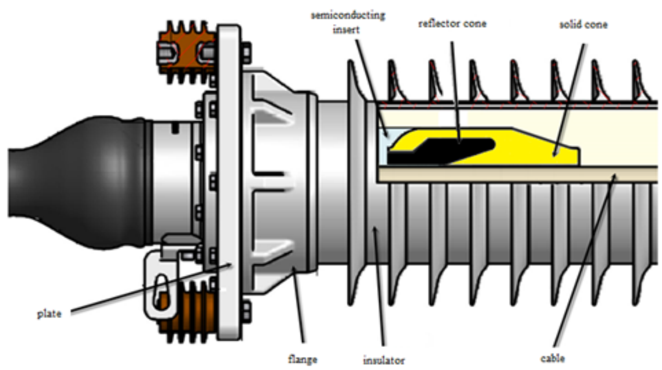

Fig. 1. Cable termination with a stress cone

We perform a number of finite element (FEA) simulations

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to obtain optimal geometry and material properties (permittivity and conductivity) of the stress cone reflector [6], [10], [11], [12].

The simulation geometry domain is shown on the fig. 2. We use triangular finite elements of the first order. The mesh density is non-uniform. It highly increases around the area where the semi-conductive coater over the XPLE insulation is broken. In the figure 2, the stress cone reflector shown in pink.

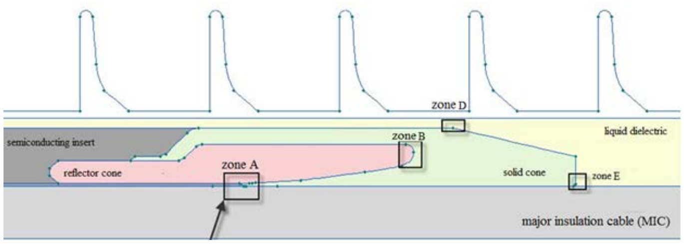

Fig.2. Geometric design model stress cone

The operating experience of the high voltage cable joints [5], [7], [8] indicates that we can identify the following problem zones in terms of strong electric field:

1) Zone of broken semi-conductive coating over the XPLE cable insulation (marked as Zone A on the figure 2)
2) The rounding area of the reflector (zone B),
3) Liquid-filled space between the stress cone and the outer insulator (zone D), and
4) The end of the cone body adjacent to the XPLE insulation (zone E).

We focus on the zone A where most defects are reported. Therefore, we choose the minimum of electric field magnitude E_A as an optimization criterion.

We adopted the one-factor-at-a-time strategy for finding the global near to optimum set of parameters [5], [10], [11], [12]. The border conditions are following: the conductor potential is equal to the peak value of the phase voltage, the screen potential is zero. The reflector part of the stress cone for its intended use must be electrically connected to the grounded screen, acting as recover of the removed original screen.

The FEA analysis of AC electric field is formulated using the phasor notation with respect to electric potential U, the current density vector $\mathbf{j}$, and electric field vector $\mathbf{E}$. The overall geometry of the cable joint is considered as axisymmetric, therefore we able to employ time effective 2D FEA calculation.

The problem formulation is based on the Gauss's law for electrostatic field [1]:

$$div(\varepsilon\mathbf{E}) = \rho, \quad (1)$$

the current conservation law:

$$div\mathbf{j} = -i\omega\rho, \quad (2)$$

the Ohm's law,

$$\mathbf{j} = \sigma\mathbf{E}, \quad (3)$$

here $\mathbf{E}$ is electric field vector, ρ is the charge density, i is imaginary unit, $i\omega$ is the phasor notation of time derivation, and σ is the electric conductivity.

The resulting equation for the electric potential U is:

$$\nabla\left(\left(\varepsilon - \frac{i\sigma}{\omega}\right)\nabla U\right) = 0 \quad (4)$$

The solution of (4) gives the electric potential U and electric field $\mathbf{E}$=-*gradU* at any point of the model.

B. Electric Field in the Cable Termination

We investigated the following design options:

Table 1

Option	Stress Cone Body		Stress Cone Reflector	
	Permittivity ε	Conductivity σ, (S / m)	Permittivity ε	Conductivity σ, (S / m)
1	1	0	1	0
2	2.5	0	2.5	0
3	22	0	2.5	0
4	22	0	2.5	0.0002

We want to know the electric field pattern in the area of breakage of the semi-conductive polymer core coating over the XPLE insulation. The electric field plot below is built over a horizontal line corresponding to the ending point of the polymer coating, where the field strength reaches its maximum.

Fig. 3. shows the electric field distribution along the horizontal line with the four design options from the table 1.

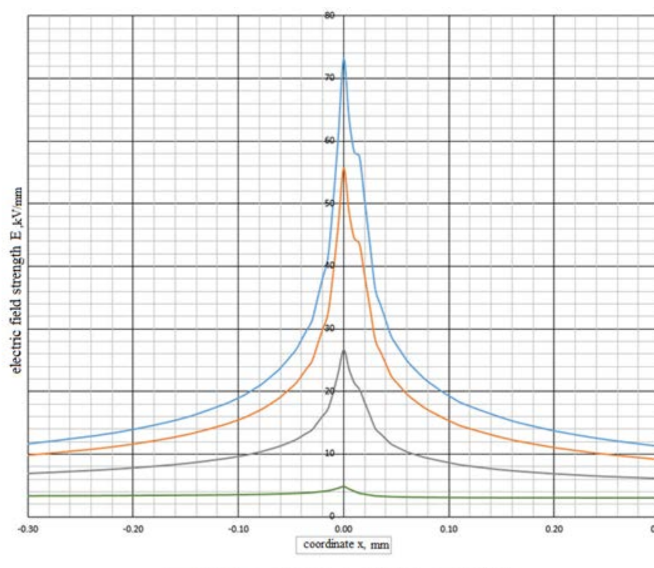

Fig.3 The field distribution in three different versions and properties of the cone reflector

Then we choose the design option that provides the greatest electric field reduction in the area A (Fig. 2), namely option 4, to see the field patterns in the other two problem areas: B (at the end of the cone reflector) and D (in a liquid dielectric). The plot of the maximum field in the zones B and D vs. the permittivity of liquid dielectric is shown in Fig. 4

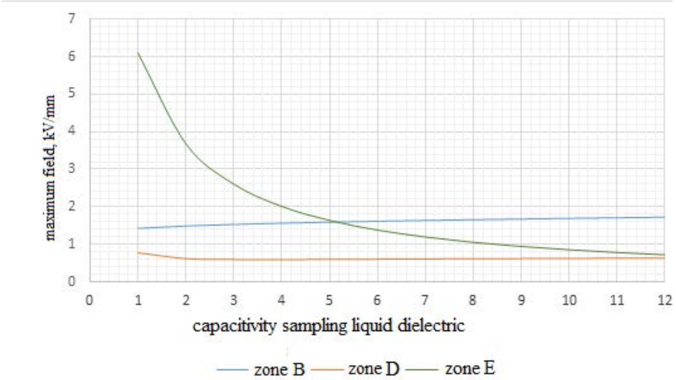

Fig. 4. Maximum field strength in areas B, D and E.

C. Electric Field in the Cable Joint.

The field grading system of the cable joint contains two double-layer conical bodies (see fig. 5) connected by a cylindrical part, which also is double layered.

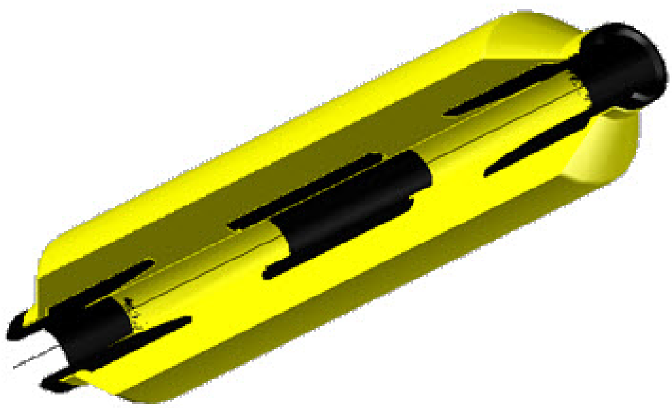

Fig. 5 The stress cone of a HV cable joint

The main insulation body is manufactured from rubber with high insulating properties. The internal layers (shown in black on the fig. 5) include two conical reflectors and a cylindrical high voltage electrode (HV-electrode) made from the molded rubber with relatively high conductance. Their role is grading of the electric field in the reinforcing insulation. The design of each reflector is similar to the stress-cone reflector of the cable termination, which was described above. Therefore, the above consideration of problem areas A and B in termination are still valid for the cable joint, where they are labeled as zone 2 and zone 2 (fig. 7). In addition, we have to focus on another problem area - the zone 3, located on the both ends of the high voltage electrode 3.

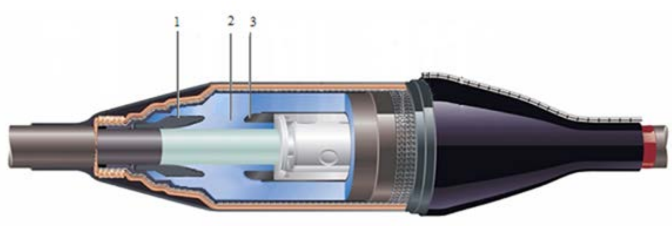

Fig. 6 Elements of the stress cone: 1 - left side reflector; 2 - main insulating body; 3 - high-voltage electrode

When the length of the HV-electrode is smaller than the length of connector, another critical area (zone 4) is detected. It locates at the edge of the connector, where the electric field is much greater than the field at the end of the HV-electrode (zone 3).

The simulation goal if finding the optimal length of the reflectors and the high voltage electrode. [7] The optimization criterion is the minimum of electric field **E** in the problem zones shown on the fig. 7.

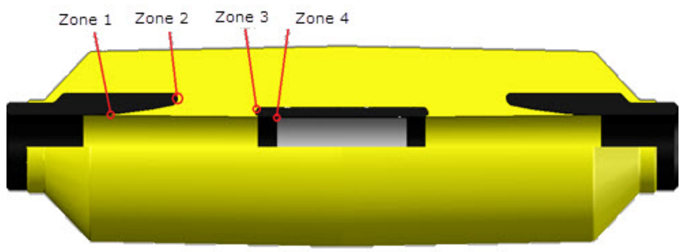

Fig. 7 The problem zones to minimize electric field: 1 – the edge of the semi-conductive layer over the insulation, 2 – reflector's edge, 3 – the edge of HV-electrode, 4 – edge of connector.

We want to find the optimal length of each reflector and the length of the HV-electrode that minimize the magnitude of electric field **E** in the problem areas 1, 2, 3, and 4.

We employ the one-factor-at-time optimization strategy. The rest of this chapter describes the series of the studies; each of them catches the dependency of magnitude of electric field **E** in one or more problem zones vs. a chosen design parameter.

1) Influence of the length of HV-electrode

We do a series of electric field FEA simulation varying the length of reflector in range 250…170 mm. The magnitude of electric field **E** was recorded at two points:

1. The edge of the HV-electrode (zone 3);
2. The edge of the connector (zone 4);

The simulation results are summarized in the table 2 and in the plot fig. 8 for the connector of 150 mm lenght.

Table 2

HV-electrode length, mm	**E, кV/mm. (by the connector length 150 mm)**	**E, кV/mm. (by the connector length 180 mm)**
200	2,78	2,69
250	2,75	2,76
300	3,03	3
350	4,69	4,69
360	6	5,95
370	8,8	8,6

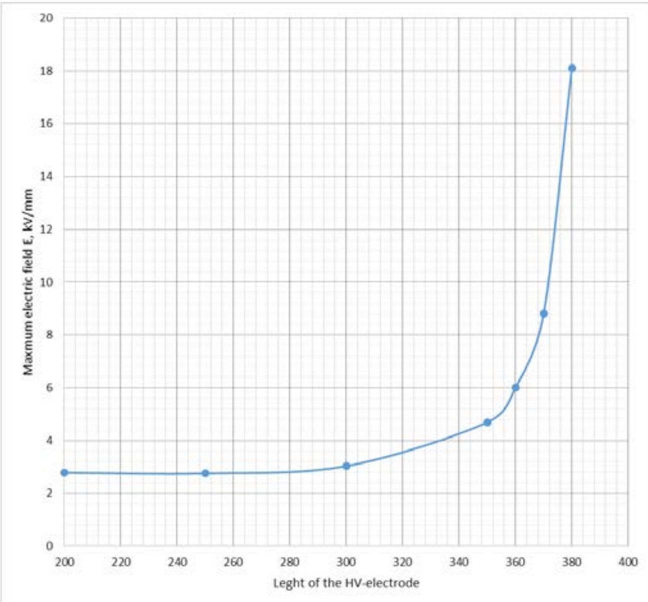

Fig. 8 The electric field E vs. length of HV-electrode

The simulation with the connector of 180 mm length, we obtain almost the same curve.

Ideally, the length of the connector have to match the length of the HV-electrode. In practice, this is not always the case, so we want to simulate carefully the electric field near the edge of HV-electrode. The typical field pattern in zones 3 and 4 is shown on the fig. 9.

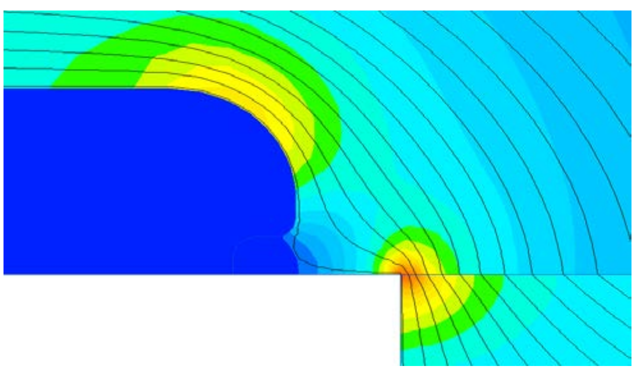

Fig. 9 The field pattern at the edge of HV-electrode (zone 3)

2) Influence of the reflector length

Varying the length of the reflector we recorded electric field at the edge of semi-conductive layer over insulation (zone 1) and at the right edge of the reflector (zone 2). Simulation results given in the table 3 and graphically on the fig. 10

Table 3

Reflector length, mm	**Electric field** E**, kV/mm**	
	Zone 1	**Zone 2**
250	4,89	1,17
230	4,86	1,23
210	4,82	1,25
190	4,75	1,26
170	5,00	1,33

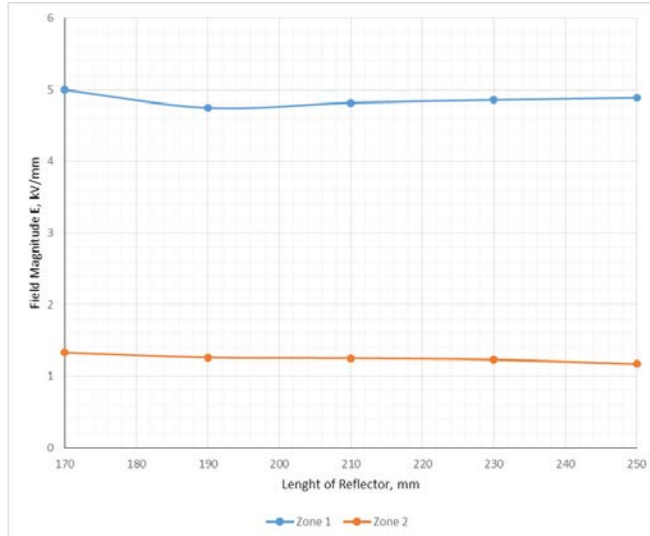

Fig. 10 Field in zones 1 and 2 vs. the length of reflector

3) Influence of the reflector angle

The next parameter to vary is the angle of reflector cone. The numerical study shows that the maximal value of electric field **E** increases almost proportional to the cone angle in the initial part of the curve on fig. 11.

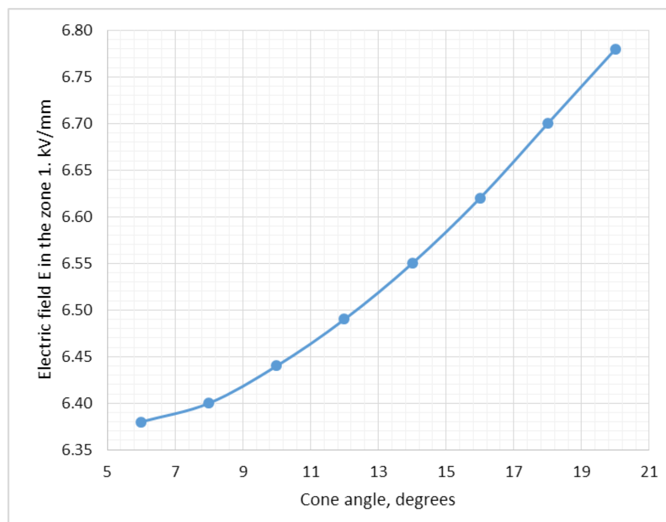

Fig. 11 The electric field **E** in zone 1 vs. angle of reflector cone in degrees.

That means that the angle should be chosen as small as it is possible by manufacturing reasons.

4) Influence of the distance from reflector to HV-electrode

It is also interesting to know the optimal reflector to HV-electrode distance. The typical field pattern shown on the fig. 12.

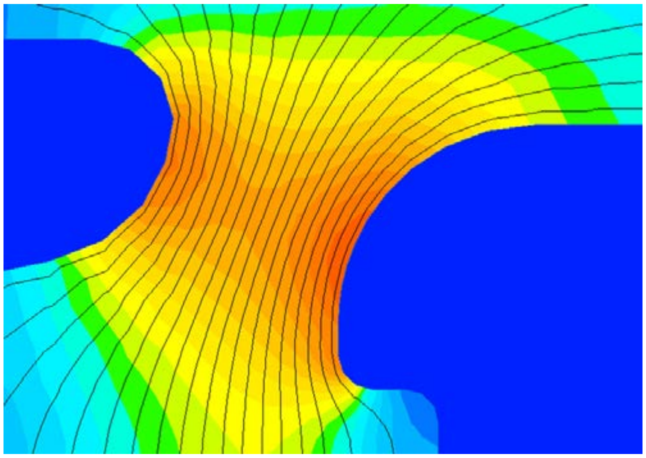

Fig. 12 Electric field between reflector and the HV-electrode. The distance is 65 mm. The most dangerous region is shown in orange color

The field values recorded in zones 1 and 2 are summarized in the table 5 and graphically on fig 13:

Table 5

Reflector to HV-electrode distance, mm	Electric field E, kV/mm	
	Near reflector (zone 1)	Near HV-electrode (zone 2)
65	1.10	2.78
55	1.20	2.80
45	1.47	2.93
35	1.91	3.12
25	2.67	3.51
10	5.50	6.00

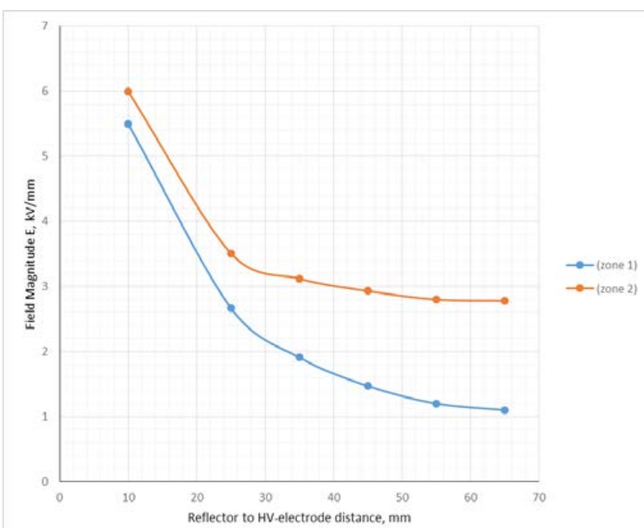

Fig. 13 Electric field **E** vs. the distance between the reflector and the HV-electrode

5) Influence of the conductivity of HV-electrode

The last varying parameter is the conductivity of the HV-electrode. It mostly affects to the field value in zone 3. The simulated E-field vs. conductivity curve is shown on the fig. 14

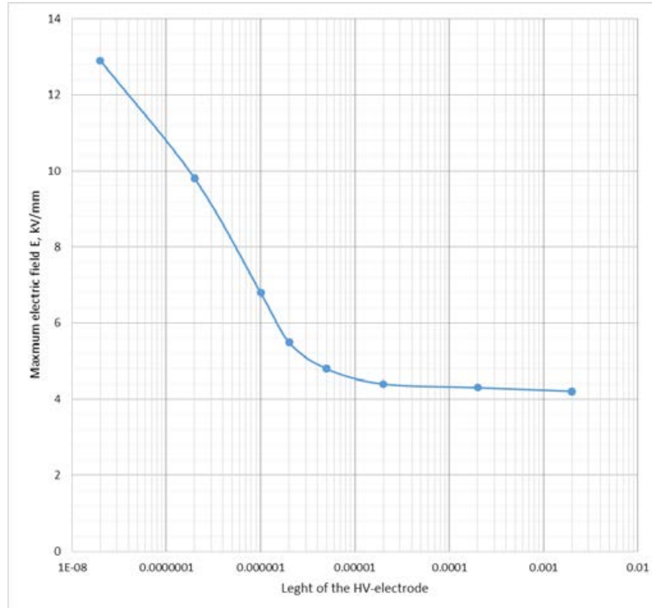

Fig. 14 Electric field E in zone 3 vs. conductivity of HV-electrode

The curve on the fig. 16 shows that the electric field decreases with increased conductivity until the later reaches $2{\cdot}10^{-4}$ S/m. Further increasing of the conductivity has no significant effect. We can guess that the same is true for the field in zone 1 (near reflector). Typically he same material is chosen for both reflector and HV-electrode.

III. Resistive Field Grading.

A promising alternative to the capacitive stress grading with specially profiled stress cones is the resistive grading [1], [2], [13]. It is essentially the increasing of the longitudinal conductivity in cable joint or termination, and can be implemented by coating the XPLE cable insulation with one or mode semi-conductive layers.

We consider a single layer coating over the insulation, called as *field grading tube*.

To simulate the effect of the parameters of the field grading tube we consider the following simplified model of the cable termination (fig. 15):

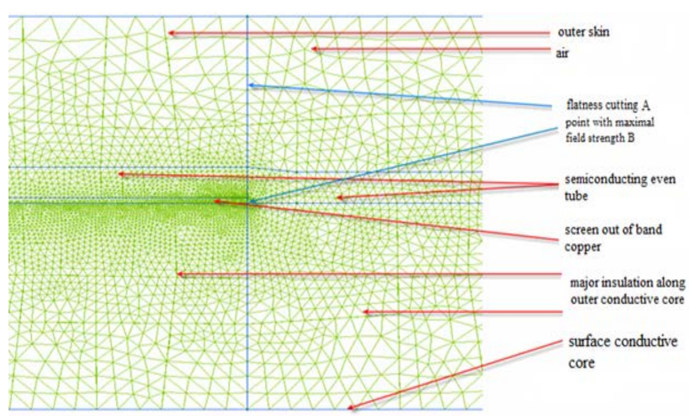

Figure 12 Calculation model cutting

There is a longitudinal sectional view of the cable [9] to the cutting of the outer shell.

The vertical line (indicated in blue) is a trace of the cutting plane A. To grading the electric field the XPLE insulation is coated by the semi-conductive tube with nonlinear electrical properties. The FEA simulation shows that the maximum magnitude of **E** field arises in the intersection of the plane A with the outer surface of XPLE insulation (point B).

The goal of analysis if finding the dependency of maximal electric field **E** on the conductivity of the grading tube. In this study we consider the field independent conductivity for sake of simplicity. In the future, it is necessary to take into account the nonlinear properties of the grading tube, picking up these properties in accordance with the information about the state of the insulation terminal or coupling [14],[15].

The simulation results of maximum electric field magnitude in point A and B (see above) vs. the conductivity of grading tube are presented in fig. 16

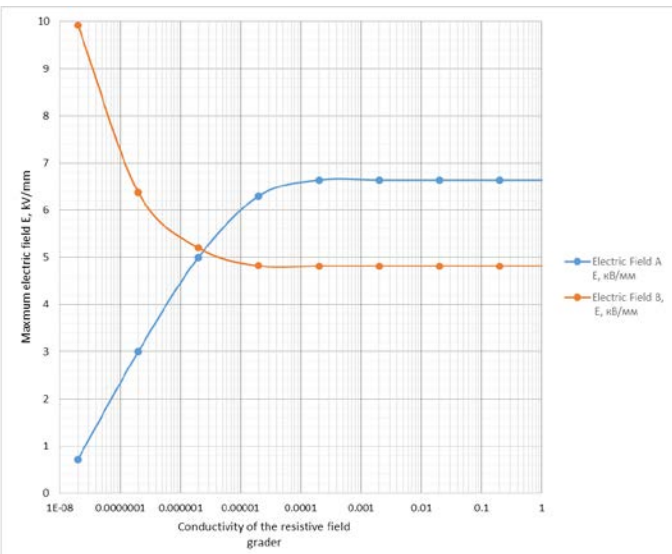

Fig. 16. Maximum electric field vs. conductivity of grading tube

IV. Conclusion

The paper describes a method for electric field grading at the end of the cable conductor, the shield and the semi-conductive coating. The method is based on a combination of material properties and the shape of the stress cone. The most dangerous area in the cable termination and joint are identified. FEA simulation of the electric field over dangerous areas is done with varying of geometric parameters and permittivity and conductivity of materials:

The most important results are following:

- The optimal shape of a semi-conductive reflector is a hollow cone with a specially selected length and the cone angle.
- The optimal value of the cone aperture is in range φ = 8... 14.
- The optimal permittivity of the main insulation body of the stress cone is in range ε = 22...24.
- Comparing to cable termination, cable joint involves additional parameters to optimize. Recommendations are given concerning the length of the central high-voltage electrode.
- The possibility of using the same HV-electrode with connectors of different length are investigated. This study suggests when the same stress-cone can be safely used with different connectors. It may also lead to reducing the overall length of the cable joint.

Normally the mixture of an elastic polymer material with a conductive particulate filler can be used for the reflector.

When the line voltage is far from be pure sinusoidal, the refractive stress grading may be less effective. In such case the combination of geometrical and impedance stress grading method is applicable.

The FEA model of the impedance field grading method is proposed. The dependency of field grading effectiveness vs. the conductivity of grading tube is given. The using of stress grading tube with field dependent conductance is a subject of further investigation.

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