Capacitance and Impedance Methods of Electric Field Grading in Cable Joint and Termination

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***Abstract*—** Designing and manufacturing of competitive cable joints and terminals is one of the most complicated high-tech challenges in the modern cable industry. The known methods for electric field grading are based either on proper selection of the geometric configuration and physical properties of the stress cone, or on controlling the field within the tube coupling. We propose the new capacitive method that combines advantages of geometric and refractive methods, as well as stress control method by resistive tube regulator. The optimal configuration of the active elements and properties of materials is proposed, which is based on the FEA simulation of the electric field.

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.

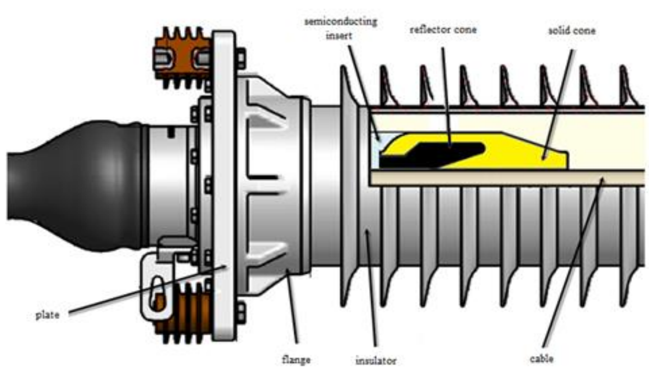

Fig. 1. Cable termination with a stress cone

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.

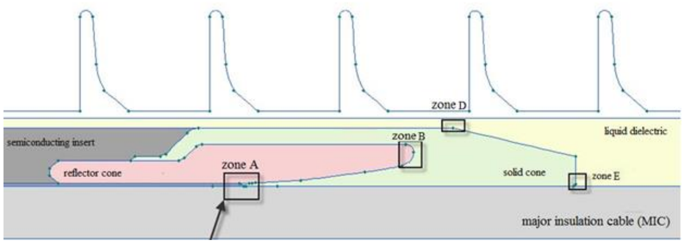


Fig.2. Geometric design model stress cone

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 **j**, and electric field vector **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]:

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

the current conservation law:

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

the Ohm's law,

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

here **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:

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

The solution of (4) gives the electric potential U and electric field **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.

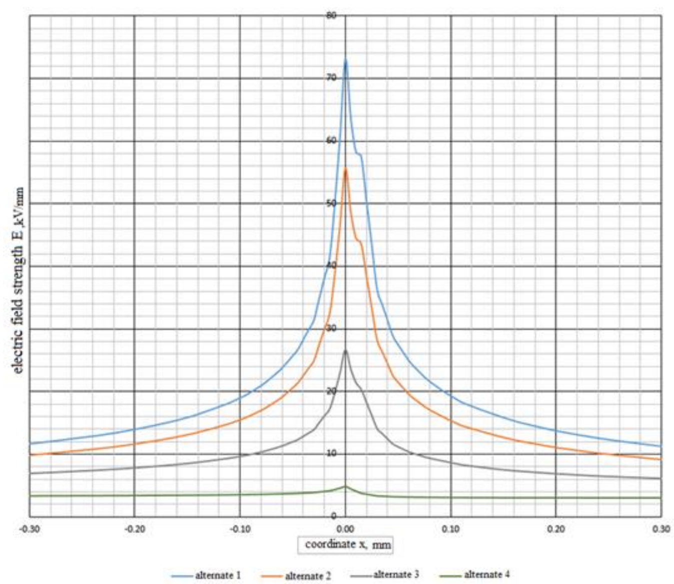


Fig.3 The field distribution in three different versions and properties of the cone reflector

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

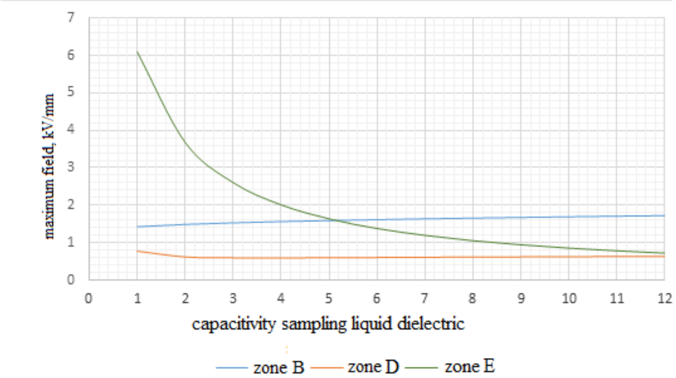
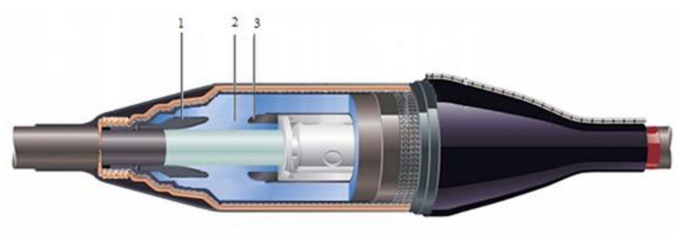


Fig. 4. Maximum field strength in areas B, D and E.

C. Electric Field simulations in the Cable Joint.

The field grading system of the cable termination is a bit more complicated than one of the cable joint we consider eaarlier. It contains two double-layer conical bodies (see fig. 5) connected by a cylindrical part, which also is double layered. The main body is manufactured from rubber with high insulating properties. The internal layers (shown in black on the fig. 5) include two cones (deflectors) and a cylindrical high voltage electrode are 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 deflector is similar to the stress cone reflector of the cable termination, which was described early. Therefore, the above consideration of problem areas A and B are still valid for the cable joint. In addition, we should focus on is another problem area - the zone C, located on the ends of the high voltage electrode.

The purpose of modeling - finding the optimal length of the baffle and the high voltage electrode. [7] Criteria - minimum electric field strength in the areas A, B and C.



1 - left side deflector; 2 - main insulating body; 3 - high-voltage electrode

Fig. 5 Stress cone coupling

We want to find the optimal length of each deflector and the length of the high-voltage electrode that minimize the magnitude of electric field **E** in the problem areas A, B and C. The FEA formulation (4) is used in an axisymmetric geometry domain. We have varied the length of the reflector in range from 250 mm to 170 mm with the step 20 mm. The electric field magnitude was recorded at two points:

1. Ending point of the semi-conductive coating over XPLE insulation, labeled as **P**;
2. Ending point of the reflector, which is the closest to the high voltage electrode, labeled as **Q**;

Table 2

The length of the Reflector, mm	E, кV/mm at the point P	E, кV/mm at the point Q
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

If the length of the high voltage electrode is smaller than the length of the sheath, another critical area is detected. Is locates at the edge of the liner, where the electric field is much greater than the field at the end of the high voltage electrode.

The simulation results are summarized in Table 3

Table 3

The length of the high voltage electrode, mm	E, кV/mm. (near electrode)	E, kV/mm. (at the edge of the conductive sleeve)
280	5.11	0.0001
260	4.8	0.0008
200	4.79	0.0024
180	4.71	0.017
160	4.75	0.2
140	4.61	7.84

III. IMPEDANCE METHOD OF ELECTRIC FIELD GRADING.

A promising alternative to the capacitive stress grading with specially profiled stress cones is the impedance method. 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. 6):

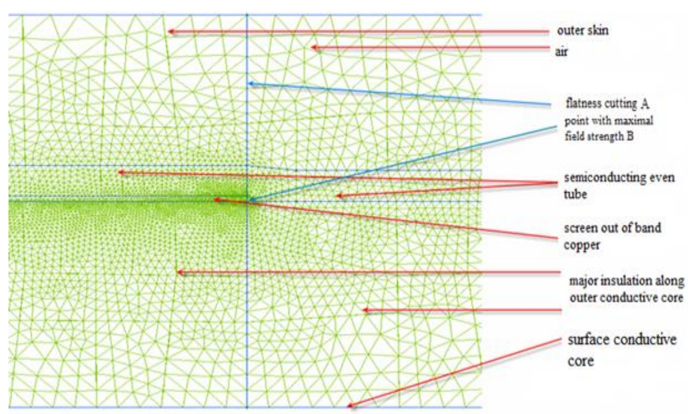


Figure 6 Calculation model cutting

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 conductivity as a constant in sake of simplicity.

The simulation results are presented in fig. 7

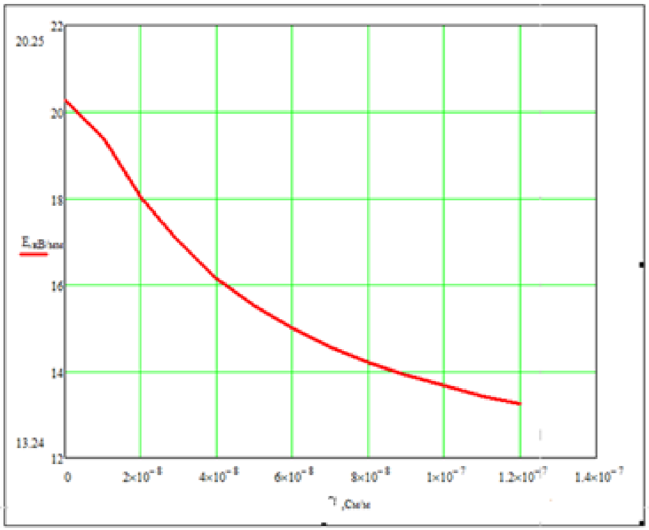


Figure 7. Maximum electric field vs. conductivity of grading tube

IV. Conclusion

The paper describes a method for electric field grading at the end of cable conductor, shield and 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 at a fixed angle between the generatrix and the longitudinal axis of the cable.
- 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.

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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