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Analysis of Design of MV XLPE Cable Termination with Embedded Electrode

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Abstract: The application of embedded electrode (EE) in MV XLPE cable termination strongly affects the electric field around the termination and accordingly must be carefully considered. In this paper, the influence of embedded electrode on voltage distribution in some constructions of 20 kV cable termination are analyzed, taking into account effect of grounding the EEs, such as different position and mutual distance, even a number of them along the cable insulation surface. In all of them, the basic method of the stress relieving with resistive layer over the end of semi conducting screen and primary cable insulation is applied. Reference design is the cable termination without EE, which voltage, total and tangential electric field distributions are observed. The stress relief materials, in the shape of the pad or tube, are used and their properties remain the same in all construction. The effect of EE application on the cable termination property is estimated by comparing the curves of voltage distributions along the cable insulation surface between the semi conducting screen end of the cable insulation at ground potential and end of primary insulation in the vicinity of phase conductor. At the very end of this paper, application of EE is summarized, both from numerical and practical points of view, in order to answer how EE is useful for stress relief in the cable terminations.

Key words: Cable termination, stress relief, embedded electrode, voltage distribution, electric field, tangential electric field.

1 Introduction

Nevertheless the voltage level in the cable network for electric power supply, each cable line, beside the cable itself, consists of two cable terminations (CTs) and arbitrary number of cable joints, depending on the cable route length, which may be several kilometers long. The cables are typically produced up to 1 km long sections, wound on the cable drum, so that in the case, when the route length is shorter than factory cable length, there is no need to include cable joint. The cable terminations are assembled at the ends of cable line and can be both for indoor or outdoor mounting. There are many techniques in the practice for jointing and terminating the power cables [1-3], but the most preferable is heat shrinkable (HS) one. Compared to the cables, cable accessories (joints and terminations) consist of more different dielectrics, which physical and electrical properties differ to the basic dielectrics, applied in the cables (for instance, stress relief material). Sometimes, EEs or semi conductive parts could be also included in the cable accessories, to modify electric field map and reduce its magnitude [4]. In spite of trends that main parts of the cables accessories shall be prefabricated ones, to avoid possible influence of human factor and also that there are many additional tools for preparing the cable ends for jointing and terminating, there still must be manual work during the installation process. In this way, some microscopic air bubbles necessarily could remain in the interface between dielectric layers, causing the local discharges under the both electric and thermal field in the first time and later on, if conditions get worse, to breakdown or flashover. Therefore, partial discharges are allowed up to the determined level, which must not be overcome. Taking into account that the jointer work cannot be perfect during the assembling process, and the construction of the cable accessories is more complicated than the cable, it can be concluded that the cable terminations, such as joints, represent weak spots on the cable line.

2 Theoretical description

From a dielectric point of view, the critical zone in each screened cable termination (for voltages above 1 kV) is interrupt of semi conducting cable screen, where electric field lines are particularly constricted. Due to complexity, the electric field magnitude cannot be calculated by analytical methods, except in the case of geometric stress relieving by stress cone, however, the most efficient and frequent way is some of the many numerical methods, such as finite element method (FEM), method of integral equations, equivalent electrode method, etc. Nevertheless, the problem solving is much easier, since the system of dielectrics and electrodes in the cable termination is symmetrical in axial direction, which means it becomes two dimensional one.

Modeling of cable terminations is very complex problem especially, when the analyzed system, being rotationally symmetrical, consists of more electrodes and more different dielectrics. In the case of non-linear or anisotropic materials for stress relieving, additional problems in solving may be occurred. By modeling, the service conditions of cable terminations could be simulated and the high costs of experiment, as way of investigation could be avoided. Therefore, numerical modeling plays so very important role in this analysis.

Available software is used for preprocessing and post processing the data, as well as for automatic grid generation. Unknown variable, electric potential V can be determined by solving two dimensional Laplace's equation in cylindrical coordinates, which is for axisymmetric case:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\varepsilon_r r\frac{\partial V}{\partial r}\right)+\frac{\partial}{\partial z}\cdot\left(\varepsilon_z\frac{\partial V}{\partial z}\right)=0 \qquad (1)$$

where $V = \mathrm{f}\,(r, z)$ and r - radius. The boundaries are defined by the phase conductor potential, V_1=10 kV and the screen ground potential V_2=0. Equipotential map is generated using finite element method (FEM) and the electric field was calculated from the corresponding potential. In this way Laplace’s equation is satisfied in each point of the observed system [5].

Relevant material properties, such as geometric characteristics of the cable and termination, are shown in the Tables 1 and 2, respectively. Note, that the electrical properties of stress relief layer, indicated in the Table 1, were obtained by DC and AC measurements. Some properties, like permittivity of semi conducting layer and metals, were supposed to be 100 and 1000, respectively, because of common behavior of such materials. These values, represented herein, were used to feed the models for the voltage distribution calculation [6,7].

Table 1. The electrical properties of the main materials

	XLPE	EPR	RZGO	Air	SC screen	Metals
Volume resistivity ρ (Ω cm)	10^{16}		$2 \cdot 10^{14}$	10^{18}	200	$1.724 \cdot 10^{-6}$
Loss angle tgδ	10^{-4}	10^{-3}	0.101	10^{-4}	-	-
Relative permittivity ε_r	2.3	3.4	10.6	1	100	1000

Table 2. Design of the cable and cable termination

Cable			Cable termination	
Conductor	Cross section (mm^2)	120	Type	Indoor, heat shrinkable
	Material, shape	Al, round	Type of connection	Cable compression type terminal lug, made of Al (could be bimetallic)
	Diameter (mm)	13.7	Type of stress relief	Resistive, stress relief pad – RZGO, thickness 1 mm
Conductor and insulation screen	Thickness (mm)	0.5	Outer protection	Dual wall HS tube, consisting of outer XLPE layer+inner EPR rubber
XLPE insulation	Thickness (mm)	5.5		
	Diameter (mm)	26	Ground wire	Yes
Copper screen (Cu tapes + wires)	Cross section (mm^2)	16	Length of cable insulation, covered by stress relief pad (mm)	100
Outer PVC sheath	Thickness (mm)	2.0	Total length approx (mm)	350
	Diameter (mm)	34		

The aim of further investigation are cable terminations with EE at different position along the cable insulation, various number of EE, such as their different mutual distances.

3 Analysis of Cable Termination Construction

A reliable cable termination shall have a good performances in the exploitation under the load, without overheating the connecting element, partial discharge, leakage current and erosion of the insulation surface at creepage distance.

The basic aim in the designing the cable terminations is to reduce maximum electric field magnitude inside their dielectric system as much as possible to prevent overheating and accelerated ageing of the termination, hence to make the whole cable line more reliable for electric power supply. Depending on the voltage level, the semi conducting medium voltage cable screen over insulation at ground potential (0% U_n) must be removed from the ends of cables at the safe distance from the cable conductor at phase potential (100% U_n). In this region, in distinction from the cable, where only radial component of the electric field exists, there are both radial and tangential components.

The voltage distribution from the semi conducting screen end to the end of primary insulation near the phase conductor along the cable insulation surface was found to be the most important parameter, while comparing the different constructions.

The second relevant parameter is tangential component of the electric field. It may be the reason of many problems in the service of HS CTs, because it acts along the interface of two dielectrics, in the direction in which the dielectric strength is significantly lower than those one in the radial direction. Besides, some microscopic air bubbles and particles, remaining after the shrinking the insulation tubes, additionally decrease dielectric strength in axial direction, causing initial erosion condition.

2.1 Reference design

In the first step, reference construction of the HS CT, without any EE, was analyzed both numerically and experimentally. This construction is well known and widely used in the practice (Fig.1). Stress relief layer in the shape of the pad (RZGO) is wound around the cable end, covering mainly cable insulation and partly semi conducting screen end. Outer dual wall heat shrinkable tube (DW HST) is placed over the stress relief pad, performing the permanent radial pressure on the pad by rubber flexible layer. This is the typical construction for indoor mounting. In the case of outdoor termination, the additional rain sheds shall be assembled over the outer DW HST. Their number depends on voltage level in the exploitation and on the service condition.

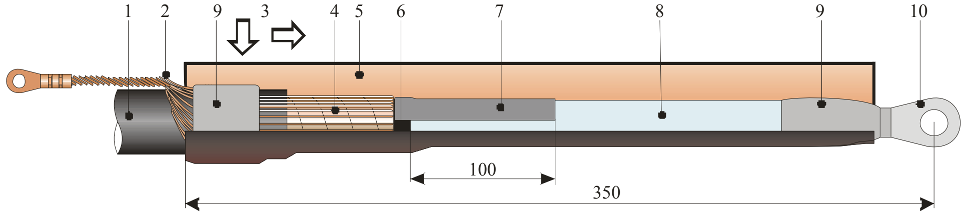


Fig. 1. Indoor HS cable termination (HS CT), assembled on MV XLPE cable 12/20 kV. (upper half refers to HS tube before shrinking, lower half after the shrinking)

Legend:

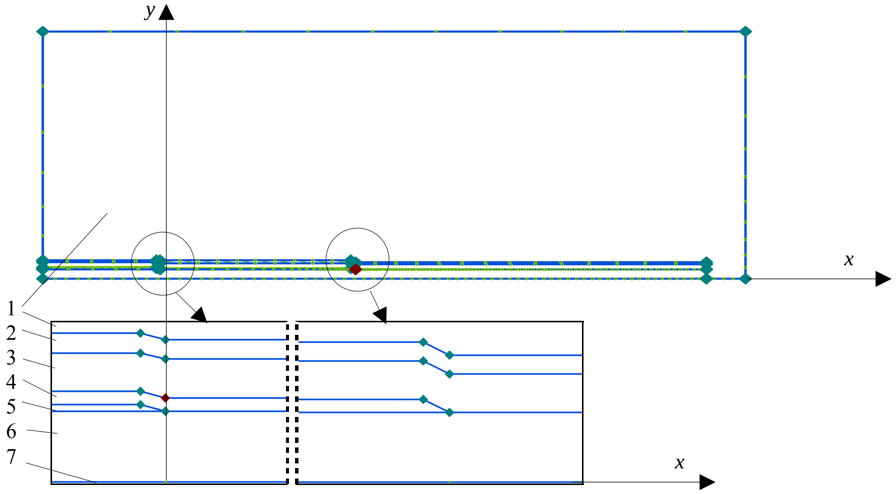
1 – Outer cable sheath
2 – Copper wire screen (ground wire)
3 – Direction of heating HS tube by burner
4 – Metallic screen (copper wires+tape)
5 – Dual wall HS tube (outer black layer of insulating XLPE and inner reddish insulating EPR)
6 – Semi conducting cable screen
7 – Stress relief pad
8 – Primary cable insulation
9 – Sealing tape
10 – Aluminium cable lug (also can be bimetallic).

Numerical modeling was primarily performed on the design of HS CT, which cross section, relevant for numerical analysis, is shown in the Figure 2.

After defining and analysis of the reference cable termination (Fig.1), further investigation will be directed to consideration of the following constructions:

1. HS CTs with EEs, made of semi conducting rubber of accepted permittivity 100. Cross section is rounded rectangle, width 10 mm, thickness 2 mm. A number and position both in radial and axial direction vary. EEs are at the floating potential;
2. The analyzed constructions are the same, but EEs are grounded;
3. Based on the results, obtained in the previous steps, some new HS CTs were suggested and analyzed in the same way;

The construction with the best performances was chosen and recommended for the application in the service.



Cross section A Cross section B

Fig. 2. Indoor HS CT, assembled on MV XLPE cable 12/20 kV.

Cross section A – end of semi conducting screen
Cross section B – end of stress relief pad

Legend: 1 – Surrounding air
2 – DW HS tube - outer insulating XLPE layer, UV protected, thickness 1,5 mm
3 – DW HS tube - inner insulating EPR rubber layer, thickness 3 mm
4 – Resistive, stress relief pad – RZGO, thickness 1 mm
5 – Semi conducting cable screen V=0% U_n
6 – XLPE insulation, thickness 5,5 mm
7 – Surface of phase cable conductor, V=100% U_n

2.2 Designs with embedded electrode (EE)

This consideration is based on the designs, which include one or more EEs [8]. Cross section A of the construction with one EE, labeled as HS CT EE1, at the distance *a* from reference point is shown in the Figure 3. When two or three EEs exist, termination is labeled as HS CT EE2 or HS CT EE3, respectively. If EEs are grounded, termination is labeled as HS CT EE [numbers of EE] grounded, otherwise, they are at the floating potential.

Parameter *a* represents distance from the reference point, such as between EEs in *x*-axis direction and was taken to be 5 and 10 mm.

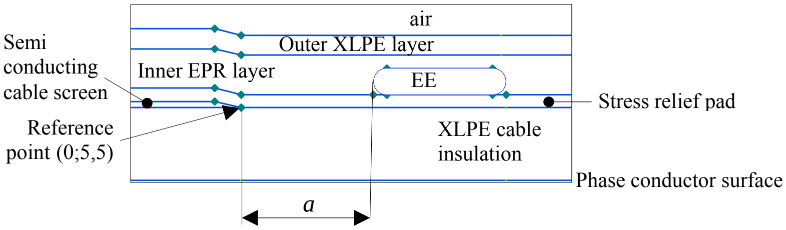


Fig. 3. Cross section A of indoor HS CT EE1, at the floating potential or grounded, for voltage 12/20 kV.

In the next step, the termination, labeled as HS CT EE [numbers of EE] r, is analyzed, where position of EEs is over DW HST. Such termination with 2 EEs is shown in the Figure 4. Parameter *a* also varies to be 5 or 10 mm and EEs are grounded or at the floating potential.

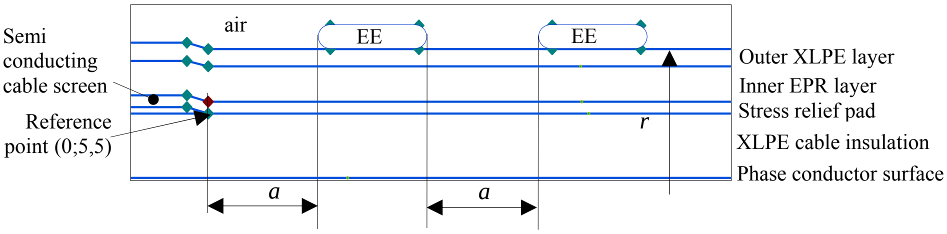


Fig. 4. Cross section A of indoor HS CT EE 2r, at the floating potential or grounded, for voltage 12/20 kV.

2.3 Designs with outer metallic and semi conducting screen

When a number of EEs is increased enough, they can be replaced with continuous grounded metallic screen, which even completely could surround HS CT. Such screen may be both in the form of stress cone (Fig.5) or outer enclosed tube (Fig.6).

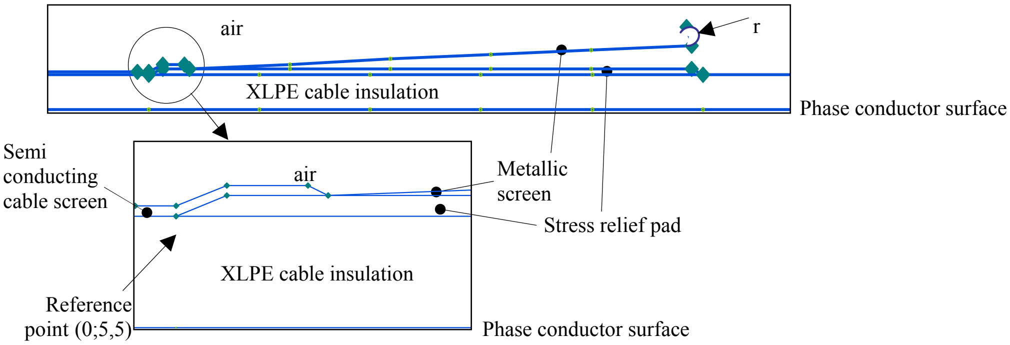
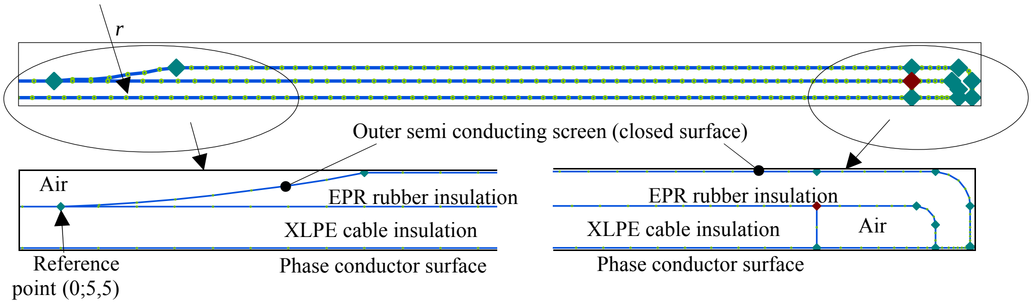


Fig. 5. Indoor HS CT EE with grounded metallic screen. Radius r=3 mm. Stress relief method is combined both geometric and resistive (labeled as CT18).



Cross section A

Cross section B

Fig. 6. Indoor HS CT EE with grounded semi conducting screen. Cone radius *r*=300 mm. Stress relief method is geometric (labeled as CT20, similar design CT19).

4 Experimental results

In the first step, some properties of the stress relief layer, were measured on the round plate with a diameter 80 mm and a thickness of approximately 1 mm. The test was performed by Megohmmeter and a Schering bridge. Since the carbon black as filler was included in the composition of the mastic for the stress relieving, it is considered as linear. This material in the form of pad 12×12 cm was applied around the semi conducting screen end, according to common principles of the stress relieving (Fig.1).

HS cable terminations (HS CT1) for indoor mounting, without EE (Fig.1), indicated as reference design, were assembled on the sample of MV cable XLPE/PVC 1×120/16 mm^2 12/20 kV according to the mounting instruction of a manufacturer [11] and subjected to test procedure, defined in some international standard. In this case, the test sequences, summarized in the Table 3, were performed according to VDE 0278, Teil 628 and 629 and carried out in HV laboratory [14]. Length of cable sample was about 7 m.

Table 3. Test Report

	Test Sequence	Prescribed	Results
1	AC Voltage Withstand Test in the dry condition (for indoor HS CT) 1 min 50 Hz	55 kV	passed
2	Partial discharge measurement at 2 U_0 = 24 kV	20 pC	20 pC
3	Lighting Impulse Voltage Test, 10 positive and 10 negative impulses	125 kV	passed
4	Heat Cycling Test with AC current at the conductor temperature 95 ^{0}C, 3 cycles (5 hours heating + 3 hours cooling)	30 kV	passed
5	Partial discharge measurement at 2 U_0 = 24 kV	20 pC	5 pC
6	Heat Cycling Test with AC current at the conductor temperature 95 ^{0}C, 60 cycles (5 hours heating + 3 hours cooling)	30 kV	passed
7	Short-time Current Test at the conductor temperature 250 ^{0}C, 1 s		passed
8	Heat Cycling Test with AC current at the conductor temperature 95 ^{0}C, 60 cycles (5 hours heating + 3 hours cooling)	30 kV	passed
9	DC Voltage Withstand Test 30 minutes	96 kV	passed
10	AC Voltage Withstand Test at 50 Hz until the breakdown or flashover, duration of each sequence 5 min	40 kV 50 kV 60 kV	passed passed breakdown after 1 min at HS CT

This testing is important to check and prove HS CT service performances, but it is carried out after modeling the same construction, described in Chapter 5. In this way, reference design HS CT1 was completely proved, before the comparison with all suggested construction.

Note, that PD level decreased after heat cycling test. Many later tests showed similar behavior, which can be explained by improvement of homogeneity of stress relief material and other dielectrics under the heating effect during the heating cycles. AC voltage withstand test in wet condition with the artificial pollution is not foreseen for indoor HS CTs, like these, so that it was not performed. After the type test, it can be concluded, that HS CTs, shown in the Figure 1, have satisfactory passed all requirements of the standard and can be used in the service for XLPE cables 20 kV. On the basis of these results, all other constructions of HS CT will be compared with reference design, described and tested above.

5 Results of numerical modeling

Analytical solution of the electric field at the conductor surface in the infinite cable gives the maximum electric field magnitude, which mustn't be overcome in any point of dielectric system of termination:

$$E_{\max} = \frac{U}{r \ln \frac{R}{r}} = 2{,}87 \ \text{kV/mm} \tag{1}$$

where:
U – phase voltage 11,6 kV (line voltage 20 kV)
R – radius over the cable insulation 12,4 mm
r – radius over the cable conductor 6.9 mm (cross section 120 mm^2).

As for tangential component of the electric field, on the basis of most practical cases of some manufacturers, it was found to be not more than 500 V/mm. All calculations in the Chapter 3 were performed for the basic voltage level 100 V. Taking into account the rate between realistic and basic phase voltage levels of 116, the basic maximum electric field magnitude and tangential electric field amount:

$$\begin{aligned} E_{\max} &= 2870/116 = 24.741\,\text{V/mm} = 24741 \ \text{V/m} \\ E_t &= 500/116 = 4.31\,\text{V/mm} = 4310 \ \text{V/m} \end{aligned} \tag{2}$$

The further numerical calculations relate to the solving the following topics:

a. influence of grounding the EE;

b. influence of moving EEs in *y*-direction

c. influence of number of EEs;

d. influence of various distances between EEs;

e. influence of outer metallic or semi conducting screen.

Hence, all analyzed terminations are summarized and labeled according to the following series:

1. Reference design CT_r without any EE, stress relieving with stress relief pad;
2. CT2 with one EE, at 10 mm from reference point (0;5.5);
3. CT3 with two EEs, at 10 mm from reference point, mutual distance 10 mm;
4. CT4 with three EEs, at 10 mm from reference point, mutual distance 10 mm;
5. CT5 with three EEs, at 5 mm from reference point, mutual distance 5 mm;

6. CT6, the same as CT2, but EE moved by 4,5 mm in *y*-direction;
7. CT7, the same as CT3, but EEs moved by 4,5 mm in *y*-direction;
8. CT8, the same as CT4, but EEs moved by 4,5 mm in *y*-direction;
9. CT9, the same as CT5, but EEs moved by 4,5 mm in *y*-direction;

10. CT10, the same as CT2, but EE grounded;
11. CT11, the same as CT3, but EEs grounded;
12. CT12, the same as CT4, but EEs grounded;
13. CT13, the same as CT5, but EEs grounded;

14. CT14, the same as CT6, but EE grounded;
15. CT15, the same as CT7, but EEs grounded;
16. CT16, the same as CT8, but EEs grounded;
17. CT17, the same as CT9, but EEs grounded;

18. CT18, without EE, stress relieving with stress relief pad and metal cone;
19. CT19, closed outer semi conducting screen, stress relieving with stress relief pad;
20. CT20, closed outer semi conducting screen, without stress relief pad.

5.1 Effect of grounding the EEs

The constructions of HS CT both with EE at floating potential and grounded EE were explored and compared to reference CT1. As the results, voltage, total electric field and tangential electric field distributions along the straight contour [(0;5.5), (280;5.5)] are shown at the graphs in the Figures 7, 8 and 9.

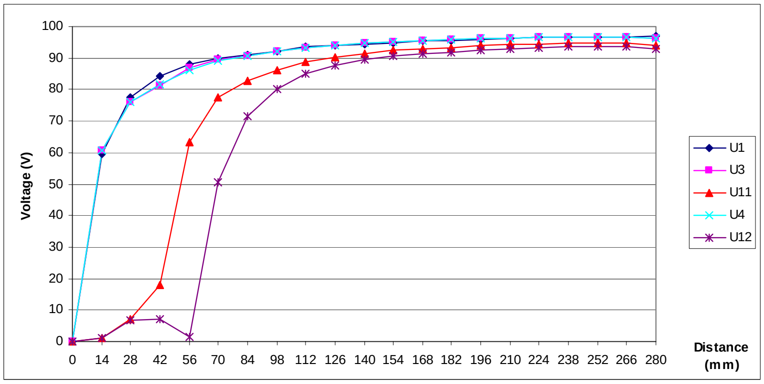


Fig. 7. Voltage distribution for terminations CT1, CT3, CT11, CT 4 and CT12.

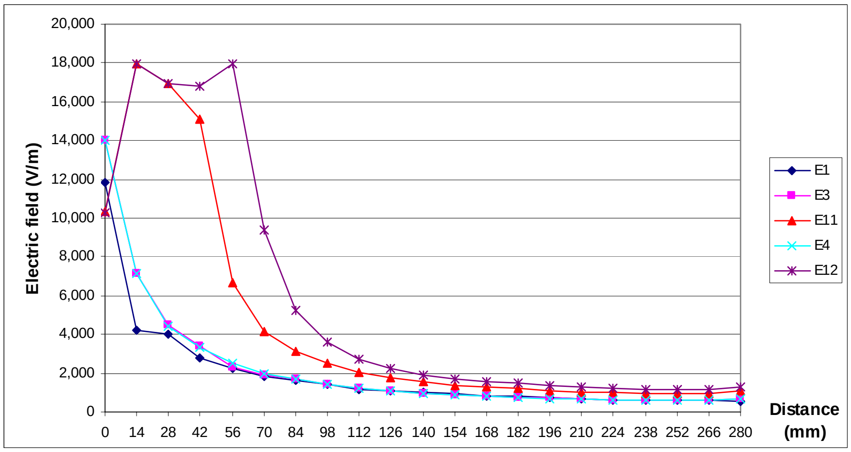


Fig. 8. Electric field distribution for terminations CT1, CT3, CT11, CT 4 and CT12.

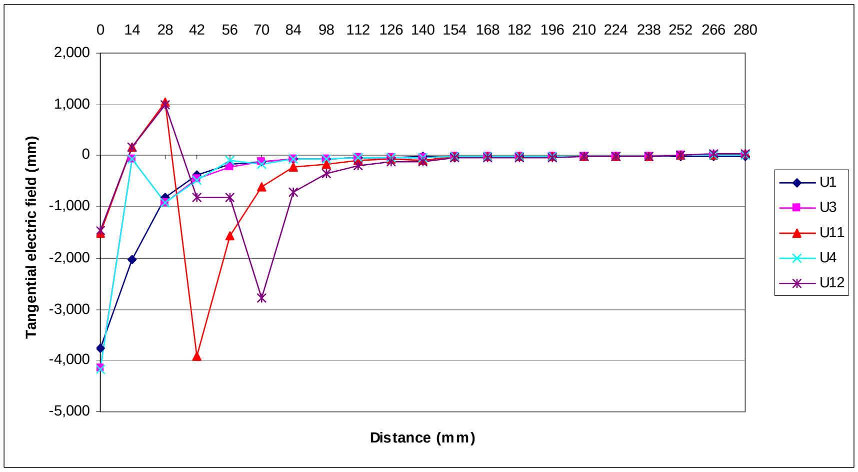


Fig.9. Tangential electric field distribution for terminations CT1, CT3, CT11, CT4 and CT12.

5.2 Effect of moving EE in *y* - direction

Practically, EE is a torus, made of semi conducting rubber, incorporated in rubber insulation, which cross section is rounded rectangle 10×2 mm. Internal diameter was primarily 28 mm and equal the diameter over stress relief pad, and than it was increased by 9 mm (in total 37 mm), which was equal the diameter over DW HST. These constructions were explored and compared to reference CT1. As the results, voltage, total electric field and tangential electric field distributions along the straight contour [(0;5.5), (280;5.5)] are shown at the graphs in the Figures 10, 11 and 12.

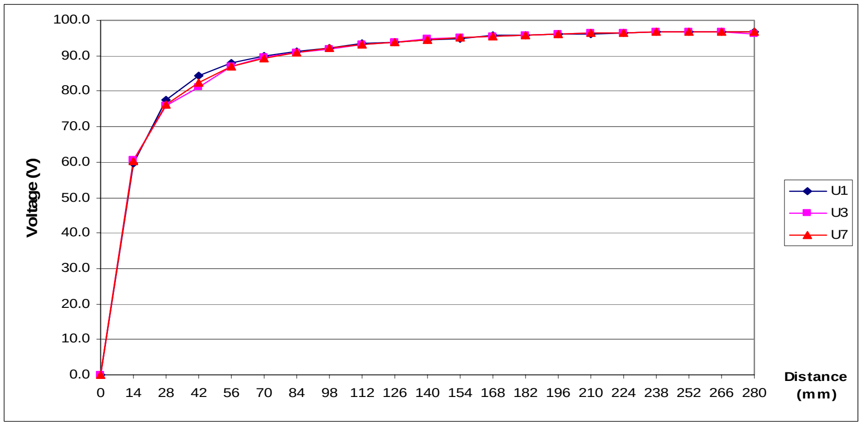


Fig. 10. Voltage distribution for terminations CT1, CT3 and CT7.

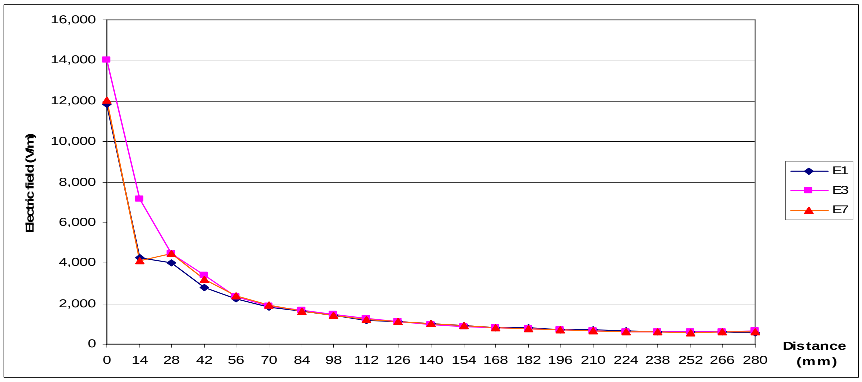


Fig. 11. Electric field distribution for terminations CT1, CT3 and CT7.

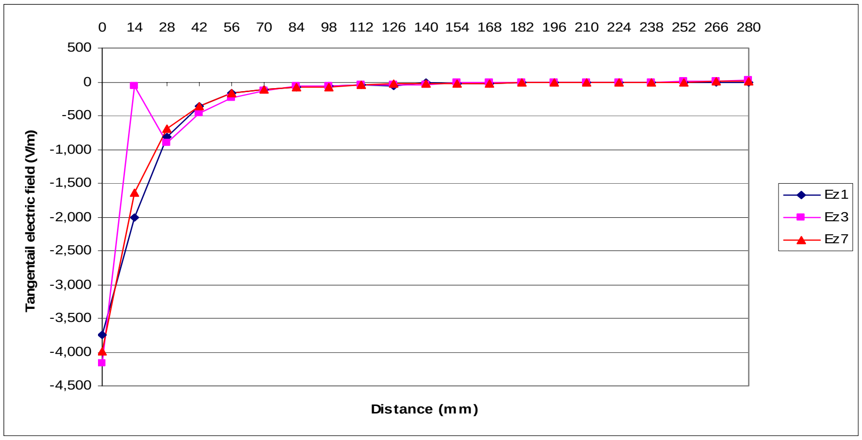


Fig. 12. Tangential electric field distribution for terminations CT1, CT3 and CT7.

5.3 Effect of increasing a number of EEs

A number of EEs was varied from 1 to 3 in axial direction at the same mutual distance 10 mm. The results are presented at the graphs below (Fig. 13, 14 and 15).

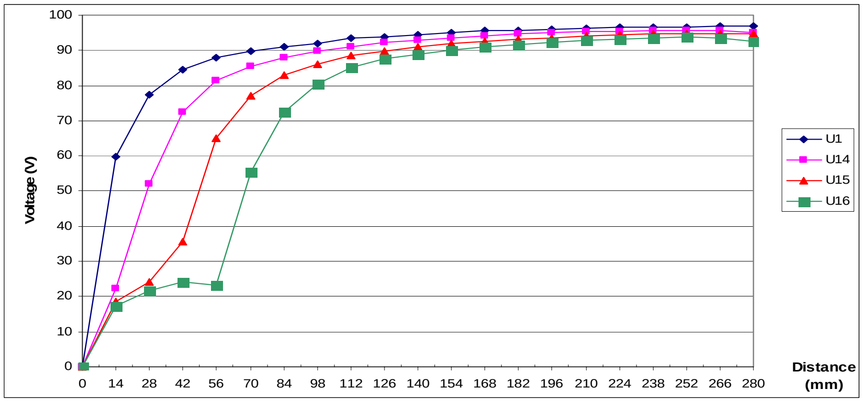


Fig. 13. Voltage distribution for terminations CT1, CT14, CT15 and CT16.

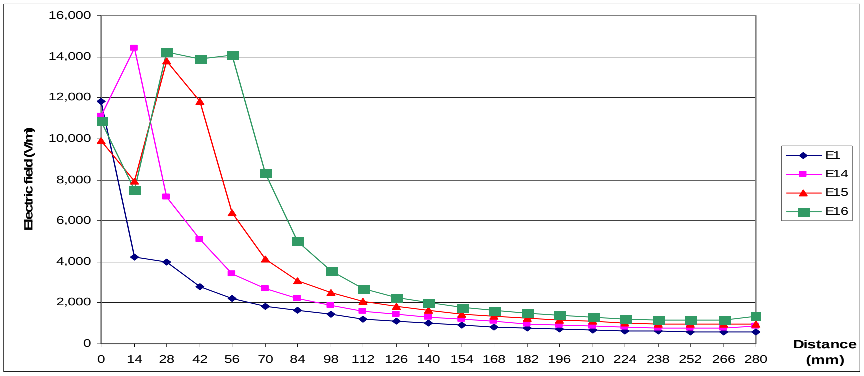


Fig. 14. Electric field distribution for terminations CT1, CT14, CT15 and CT16.

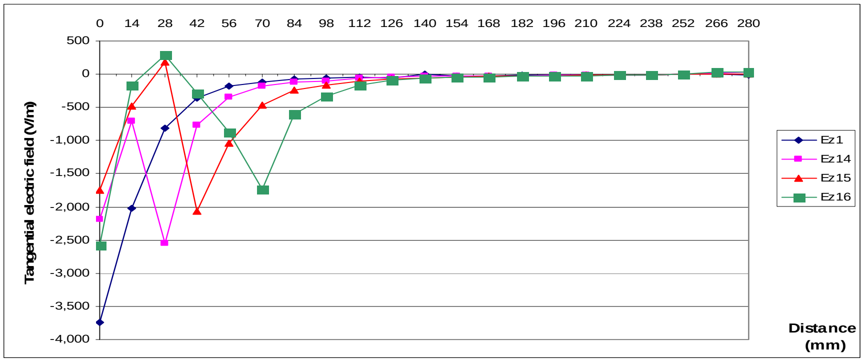


Fig. 15. Tangential electric field distribution for terminations CT1, CT14, CT15 and CT16.

5.4 Effect of decreasing mutual distance of EEs

The former mutual distance 10 mm between EEs was decreased to 5 mm. The results are presented at the graphs below (Fig. 16, 17 and 18).

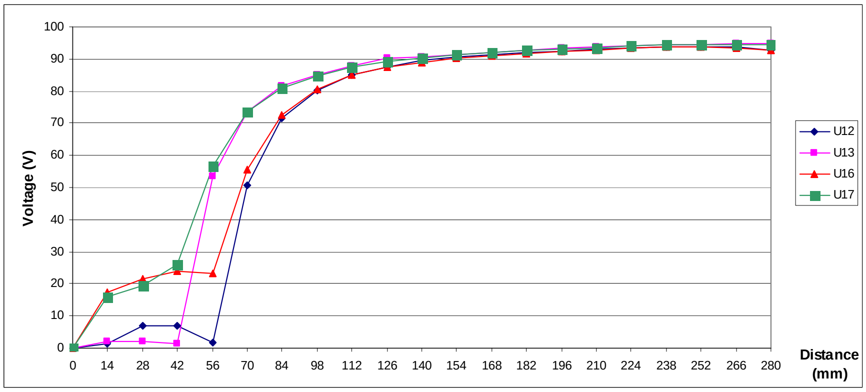


Fig. 16. Voltage distribution for terminations CT12, CT13, C16 and CT17.

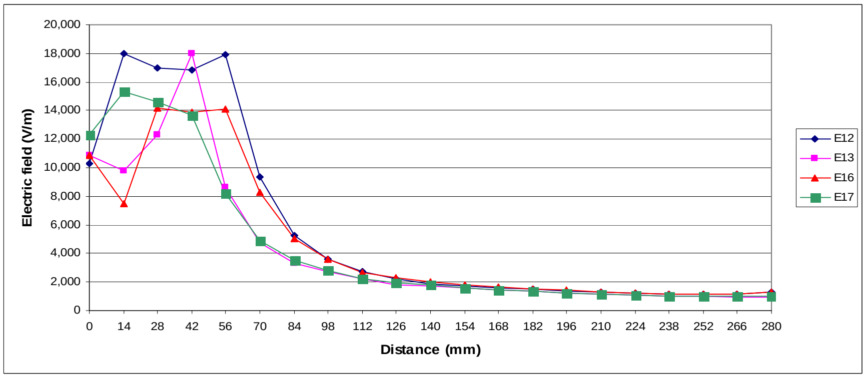


Fig. 17. Electric field distribution for terminations CT12, CT13, C16 and CT17.

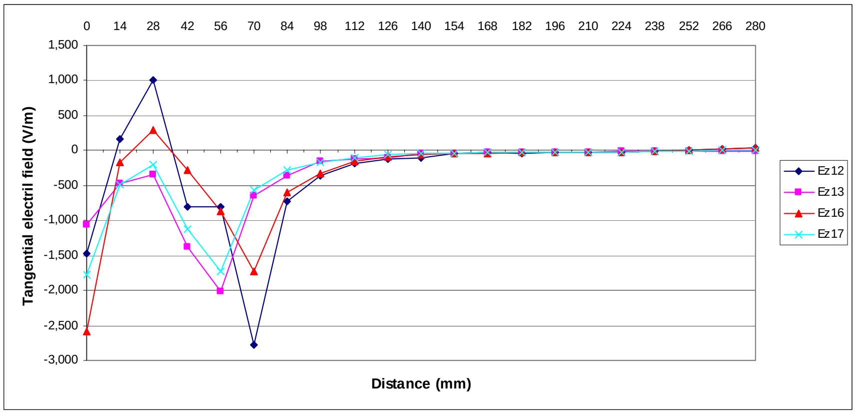


Fig. 18. Tangential electric field distribution for terminations CT12, CT13, C16 and CT17.

5.5 Effect of metal cone and closed outer semi conducting grounded screen

As dicussed in Chapter 2.3, more EEs, regularly disposed along *x*-axis, could imagine as dashed line. In the case when mutual distance between EEs becomes smaller, this line is simplified with solid line, i.e. the system of EEs convert to cylinder or cone. That means that electric field in CT18 and CT19 is controlled both geometrically and resistively. The construction CT20 was derived from CT19, but without stress relief pad and with smaller internal diameter of outer semi conducting screen (Fig.6).

The results of numerical calculation are presented at the graphs below (Fig. 19, 20 and 21).

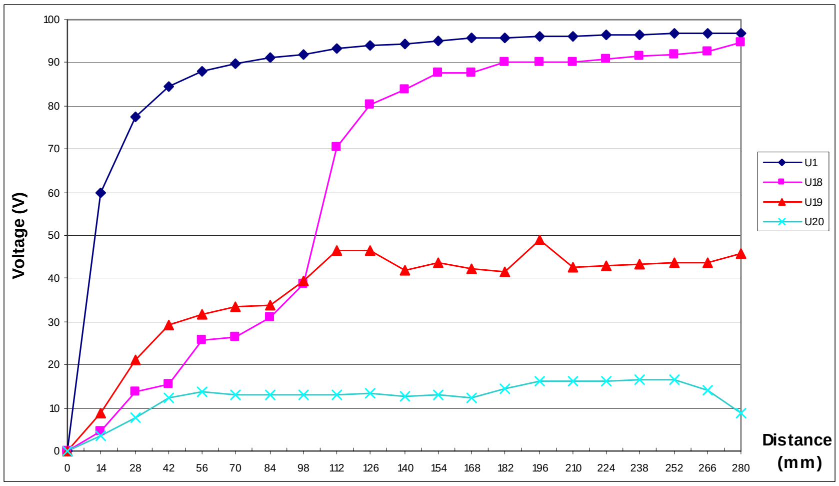


Fig. 19. Voltage distribution for terminations CT1, CT18, CT19 and CT20.

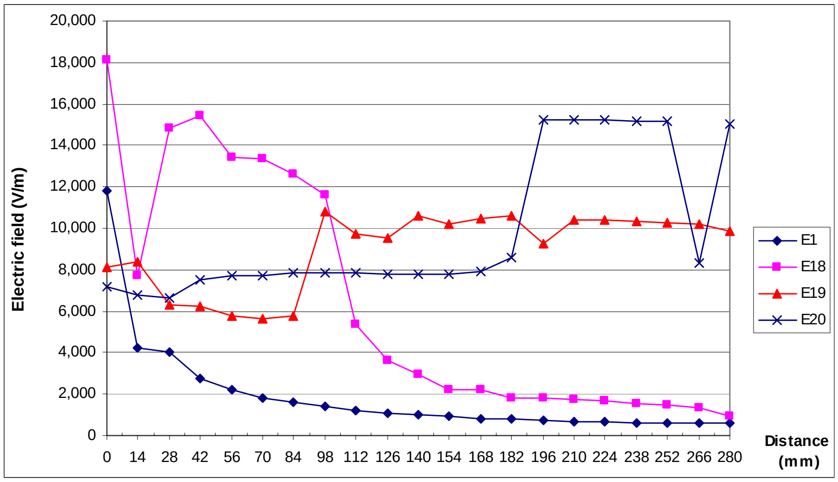


Fig. 20. Electric field distribution for terminations CT1, CT18, CT19 and CT20.

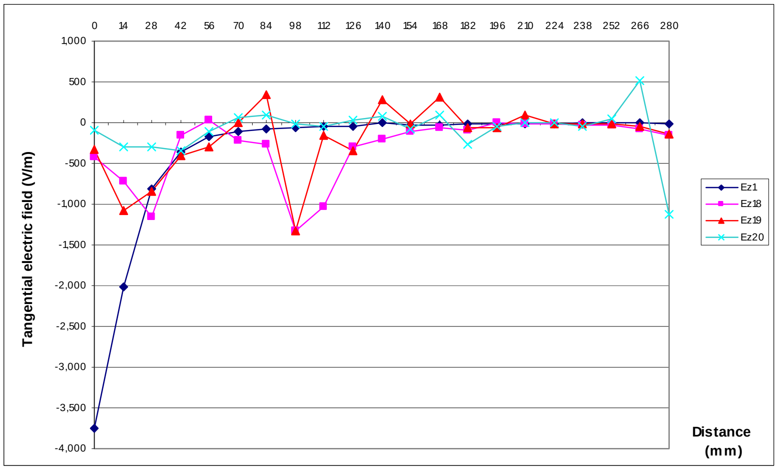


Fig. 21. Tangential electric field distribution for terminations CT1, CT18, CT19 and CT20.

6 Conclusion

The influences of EEs and other geometric and dielectric properties are as follows:

1. All explored terminations are satisfied regarding the total electric field magnitude;
2. Terminations CT2, CT5, CT8 and CT9 are not satisfied, regarding the tangential electric field magnitude and they shall be rejected;
3. Tangential electric field magnitudes in the terminations CT3, CT4 and CT6 are close to the critical value, but still acceptable;
4. EEs, both at floating potential and grounded one, strongly affect the electric field, increasing it locally, but not over the permissible values, given by (2). Voltage, electric field and tangential electric field distribution curves are shown the same gradient, compared to reference design, but in the different position along the observed contour.
5. Better performances are achieved, when EE position is over DW SHT (higher *r*).
6. More EEs generally decreased only tangential electric field. There is still local increasing the electric field magnitudes in the zone around EEs.
7. Better performances are achieved, when EEs are closer each other.
8. The best technical solution, regarding the electric field magnitudes and voltage distribution are achieved with construction CT20. It allows, that three single core terminations, belonging different phases, can be very close each other, which is of high importance for small rooms. Also, due to very small tangential electric field, the length of CT can be shortened to get very compact design, suitable for connection onto transformers, switchgears, motors and other equipment. In the case of outdoor terminations, this concept needn’t apply.
9. Based on the results above, it seems, that application of semi conductive EEs, is not justified for the analyzed constructions. For the further investigation, the solution shall be explored for the different non-conductive material and shape.

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