

Analysis of a MV XLPE Cable Termination Design with Embedded Electrodes

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Abstract: Insertion of embedded electrodes (EEs) inside a MV XLPE cable termination strongly affects electric field around the termination and accordingly must be carefully considered. In this paper, influence of embedded electrodes on voltage distribution in some constructions of the 20 kV cable terminations was analyzed. Different options were considered for a specific number of the EEs along the cable insulation surface, taking into account possible effects of floating or grounded EEs, their different position and separation. In every option, a basic method of stress relieving with resistive layer over the end of semi conducting screen and primary cable insulation was applied. Reference design was a cable termination without EE. Its voltage distribution, total electric field and tangential component were observed for comparison. The stress relief materials, in the shape of pads or tubes, were used. Their properties were kept the same in all constructions. Voltage distribution was monitored, starting from the end of the primary cable insulation in the vicinity of the phase conductor and ending at the cable insulation attached to the semiconducting screen end at ground potential. The different design options were experimentally verified.

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

1 Introduction

IRRESPECTIVE of the voltage level in the cable network for electric power distribution, each cable line has two cable terminations (CTs). They can be both

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for indoor and outdoor mounting. Cables are typically produced in up to 1 km long sections and wound on the cable drum. A cable line may be several kilometers long. Consequently, the number of cable joints is determined by the cable route length. In the case when the route length is shorter than the factory cable length, there is no need to include a cable joint. But the cable terminations are necessary at both ends of a cable line. There are many techniques in for jointing and terminating power cables [1–3], but the most preferable is with heat shrinkable (HS) sleeves. Unlike cables, with dielectric one only, the cable accessories (joints and terminations) contain more layers of different dielectrics. Their physical and electrical properties may differ very much from basic cable dielectrics. For instance, they may be made of a stress relief material. Sometimes, EEs or semi conductive parts may also be included in the cable accessories, to modify the electric field and reduce its magnitude [4]. In spite of all efforts to prefabricate the main parts of the cable accessories, thus avoiding possible influence of human factor and standardizing the tools for preparing the cable ends for jointing and terminating, there is still a lot of manual work during the installation process. If not enough care is taken, some microscopic air bubbles may remain in the interface between the dielectric layers, causing local discharges. Both electric and thermal field can escalate in time. Later on, if the conditions get any worse, this leads to breakdown or flashover. Therefore, partial discharges are allowed by cable standards up to a certain level, which must not be exceeded. The cable accessories are more complicated to produce than the cable itself. A field work of a jointer cannot be perfect during the assembling process. Consequently the cable terminations and joints may represent weak spots on the cable line. Numerical analysis has become crucial task in cable accessories design [5–9].

2 Theoretical description

Critical zone in each screened CT is the interrupt of the semi conducting cable screen. The electric field lines get particularly constricted in the neighboring cable dielectric. This is of critical importance for the voltages above 1 kV. Due to its complexity, the electric field magnitude cannot be simply calculated by analytical methods, except in the case of geometric stress relieving by a stress cone. Nowadays the most efficient and frequent way of the field calculation is by using some of the many numerical methods, such as finite element method (FEM), method of integral equations, equivalent electrode method, etc. The problem to be solved is relatively easy. Due to its axial symmetry a cable termination can be treated as a 2D problem.

Modeling of a CT is a complex task. The system to be analyzed is rotationally

symmetrical, may consist of more electrodes and more different dielectric layers. The problem gets even more challenging in the case of non-linear or anisotropic materials for stress relieving. A good numerical model can include detailed service conditions of CTs thus saving funds for the high costs of experiments.

Commercially available software was used for preprocessing and post processing of the data, as well as for the automatic grid generation. Unknown variable, electric potential V , can be determined by solving the 2D Laplace's equation in cylindrical coordinates for an axisymmetric case,

$$\frac{1}{r} \frac{\partial}{\partial r} \left(\epsilon_r r \frac{\partial V}{\partial r} \right) + \frac{\partial}{\partial z} \left(\epsilon_z \frac{\partial V}{\partial z} \right) = 0, \quad (1)$$

where $V = f(r, z)$, z is axial distance and r is radius. The boundaries are defined by the phase conductor at potential $V_1=10$ kV and the screen at ground potential, $V_2=0$. Equipotential map is generated using a finite element method (FEM). Electric field magnitude was calculated from the corresponding potential distribution. This way the Laplaces equation is satisfied in each point of the observed system [10].

Relevant material properties as well as geometric characteristics of the cable and termination are shown in Tables 1 and 2 respectively. Note that the electrical properties of the 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 taken to be 100 and 1000, respectively, because of the field canceling behavior of such materials. These values, represented herein, were used to feed the models for the voltage distribution calculation [11, 12].

Table 1. Electrical properties of the main materials.

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

Next section presents a survey on CTs with the EEs at the different positions along the cable insulator. Various numbers of the EEs and various separations between them were analyzed.

3 Analysis of Cable Termination Constructions

A reliable CT needs to have good performances in exploitation under the load. There must not be any overheating of the connecting element. No partial discharge, leakage current or insulation surface erosion is tolerated along the path that defines the creepage distance.

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 1mm
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		

Fundamental goal in designing cable terminations is to reduce maximum electric field magnitude inside their dielectric layers as much as possible. In the same time this helps to prevent overheating and accelerated ageing of the terminations. Efforts like this make the whole cable line more reliable for electric power supply. When building a termination, the cable screen must be removed from the cable end. This provides a safe distance between the semiconducting medium at ground potential ($0\%U_n$) and the cable conductor at phase potential ($100\%U_n$). Unlike inside the cable, where only radial field component exists, the CT has both radial and axial - tangential component of the field. Quality of the termination may be judged by monitoring the voltage distribution from the semi conducting screen end to the end of primary insulation near the phase conductor along the cable insulation surface. The second relevant parameter is tangential component of the electric field. It may be the reason of many problems in the service of CTs, because it acts along the interface of two dielectrics, in the direction in which the dielectric strength is significantly lower compared to the radial direction. Besides that, some microscopic air bubbles and dust particles may remain after the heat shrinking procedure, additionally decreasing dielectric strength in axial direction and causing initial erosion.

3.1 Reference design

In the first step, the reference construction of the heat shrinkable cable termination (HS CT), without any EEs, was analyzed both numerically and experimentally. This typical construction for indoor mounting is well known and widely used in

the practice (Fig.1). Stress relief layer in the shape of a pad (RZGO) is wound around the cable end, covering mainly the cable insulation and partly the screen end. An outer dual wall heat shrinkable tube (DW HST) is placed over the stress relief pad, imposing permanent radial pressure on the pad by a rubber based flexible layer. In the case of outdoor termination, an additional rain sheds must be placed over the outer DW HST. Numbers of the tubes depend on the voltage level service conditions.

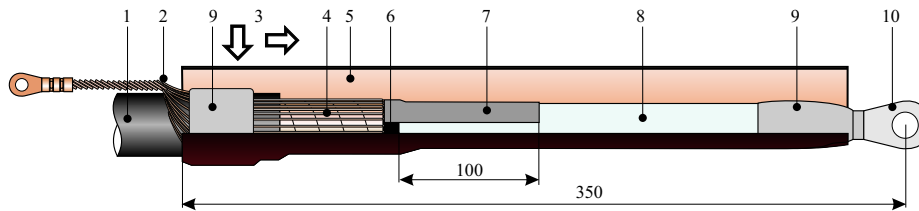


Fig. 1. Indoor HS CT assembled on MV XLPE cable 12/20 kV (upper half-before shrinking, lower half-after shrinking). Legend: 1 Outer cable sheath; 2 Copper wire screen (ground wire); 3 Desirable heating direction of the HS tube by a burner; 4 Metallic screen (copper wires+tape); 5 Dual wall HS tube (outer 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 Aluminum cable lug (also can be bimetallic).

Numerical modeling was first performed on the simplified design of HS CT, shown in the Figure 2. Further analysis included the following constructions: 1. The HS CTs with EEs, made of semi conducting rubber of relative permittivity 100. On a 2D model, a cross section of an EE is visible as a rounded rectangle, 10 mm wide and 2 mm thick. Number and position of the EEs may vary both in radial and axial direction. The EEs were at the floating potential; 2. Same as in number 1, but the EEs were grounded; 3. Based on the results from number 1 and 2, new HS CTs were proposed and analyzed.

In the end the constructions with the best performances was chosen and recommended for service application.

3.2 Designs with embedded electrodes (EEs)

Following consideration is based on the designs which include one or more EEs [13]. Cross section A, at distance a from the reference point of the CT construction with only one EE, labeled as HS CT EE1, is shown in Figure 3. When two or three EEs exist, the termination is labeled accordingly as HS CT EE2 or HS CT EE3. If the EEs are grounded the termination is labeled so, otherwise, they are at the floating potential.

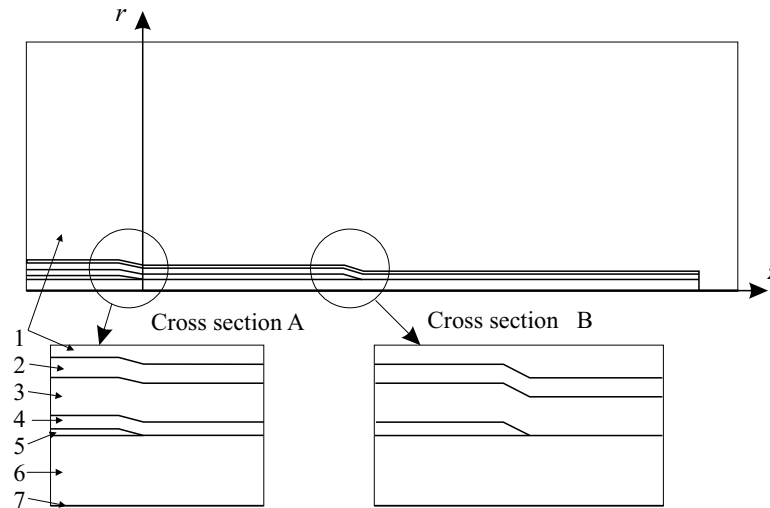


Fig. 2. Simplified indoor HS CT, assembled on a MV XLPE cable 12/20 kV. Cross section A end of semi conducting screen. Cross section B end of stress relief pad. Legend: 1 Surrounding air; 2 DW HS tube - outer insulating XLPE layer, UV protected, thickness 1,5 mm 3 DW HS tube - inner insulating EPR rubber 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, $V=100\% U_n$;

Parameter a from Fig. 3 represents the distance from the reference point to the EE in x -axis direction and was taken to be between 5 and 10 mm.

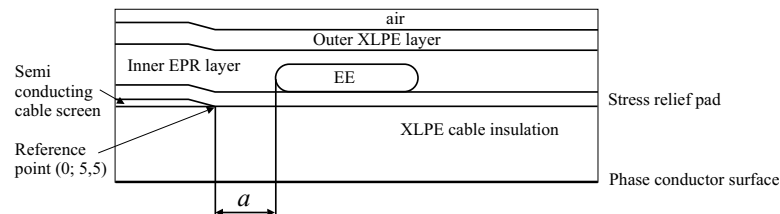


Fig. 3. Cross section A of the indoor HS CT EE1. The EE is at the floating potential or grounded.

In the next step, several EEs were inserted into the termination. The terminations were labeled accordingly as HS CT EE [numbers of EEs]. As shown in Fig. 4, the EEs were placed on the top of the DW HST. The separation a was between 5 and 10 mm. The EEs were grounded or at the floating potential.

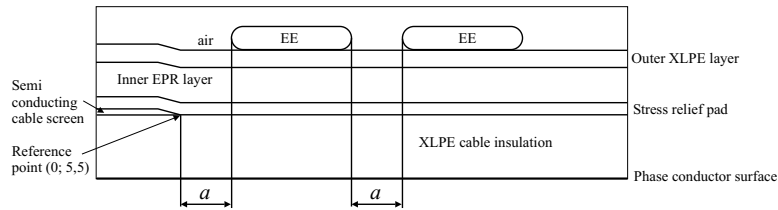


Fig. 4. Cross section A of an indoor HS CT EE 2, at the floating potential or grounded.

3.3 Designs with outer metallic or semi conducting screens

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

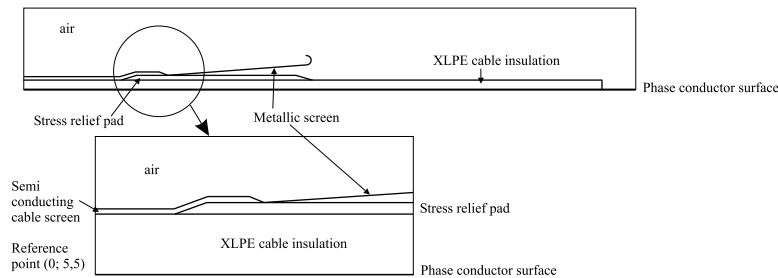


Fig. 5. Indoor HS CT with a grounded metallic screen. Radius $r = 3\text{mm}$. The stress relief method is a combination of both geometric and resistive control (labeled in the text as CT18).

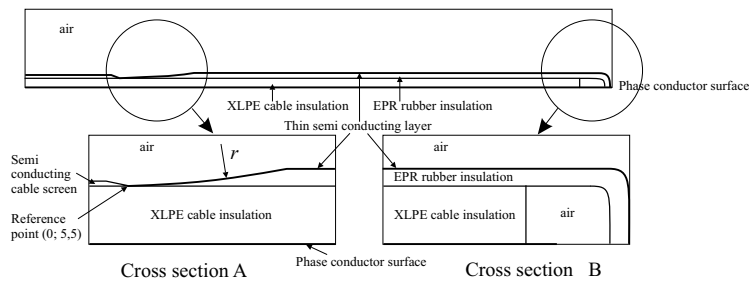


Fig. 6. Indoor HS CT with grounded semi-conducting screen. The cone radius $r = 300\text{mm}$. The stress relief method is a form of geometric control (labeled in the text as CT20, similar to the CT19).

4 Experimental results

Initially, some properties of the stress relief layer were measured on a sample in a form of a round plate with 80 mm diameter and approximately 1 mm thick. The test was performed by a Megohmmeter and a Schering bridge. Since the so called carbon black was included as filler in the composition of the stress relieving material, it is considered linear. This material in the form of a 12×12 cm pad was applied around the semi conducting screen end, according to common practice of the stress relieving (See Fig.1). Next, the HS CT without the EE, from Fig.1, was assembled as a reference design, on the sample of a MV cable XLPE/PVC 1×120/16 mm² 12/20 kV, according to the mounting instructions provided by the manufacturer [10]. The test procedure, summarized in Table 3, was performed according to standard VDE 0278, Teil 628 and 629 and carried out in the HV laboratory [14]. Available cable sample length was about 7 m.

Table 3. Test Report of a standard HS CT.

	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 $2U_0 = 24\text{kV}$	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°C, 3 cycles (5 hours heating + 3 hours cooling)	30 kV	passed
5	Partial discharge measurement at $2U_0 = 24\text{kV}$	20 pC	5 pC
6	Heat Cycling Test with AC current at the conductor temperature 95°C, 60 cycles (5 hours heating + 3 hours cooling)	30 kV	passed
7	Short-time Current Test at the conductor temperature 250°C, 1 s		passed
8	Heat Cycling Test with AC current at the conductor temperature 95°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 50kV 60kV	passed passed breakdown after 1 min at HS CT

This initial testing was important to check and confirm the HS CT service performance. Note, that the partial discharge (PD) level decreased after the heat cycling test. Many later tests showed similar behavior, which can be explained by improvement of homogeneity of the 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 was not foreseen for an indoor HS CTs like this, so that it was not performed. After the standard tests, it was concluded that the

HS CT, from Fig. 1, have satisfied the standards and can be used in service for the XLPE 20 kV cables.

All other constructions of the CTs with inserted EEs were tested according to the same procedures. Quality of the new designs was assessed based on these results compared with the corresponding results for the reference design. The first new design from Fig. 3, the HS CT1, described in section 5, was completely approved before all other suggested constructions.

5 Results of numerical modeling

Maximum allowable electric field magnitude at the conductor surface in an infinite cable can be assessed analytically as

$$E_{\max} = \frac{U}{r \ln \frac{R}{r}} = 2.87 \text{ kV/mm} \quad (2)$$

where U is phase voltage 11,6 kV (line voltage 20 kV), R is radius over the cable insulation, equal to 12,4 mm and r is radius over the cable conductor, 6.9 mm (for a cross section of 120 mm²).

The value from (1) must not be exceeded under any circumstances at any point of the dielectric system of the CT.

Regarding tangential component of the electric field, based on the most of practical suggestions by manufacturers, it should not exceed 500 V/mm. All calculations described in Section 3 were calculated for the modeling voltage level of 100 V. Taking into account the ratio between realistic and basic phase voltage levels of 116, the basic maximum electric field magnitude and tangential electric field must not exceed

$$\begin{aligned} E_{\max} &= 2870/116 = 24.741 \text{ V/mm} = 24741 \text{ V/m}, \\ E_t &= 500/116 = 4.31 \text{ V/mm} = 4310 \text{ V/m} \end{aligned} \quad (3)$$

Further numerical calculations were necessary to understand the following:

- a. influence of grounding the EEs,
- b. influence of shifting the EEs in y-direction;
- c. influence of the number of EEs;
- d. influence of various separations between the EEs;
- e. influence of the outer metallic or semi conducting screen.

All analyzed termination designs are summarized and labeled according to the following:

1. Reference design CTr without any EEs. The electric stress was relieved using the stress relief pad;
2. CT1 with one EE, at 10 mm from the reference point (0;5.5);
3. CT2 with two EEs, at 10 mm from the reference point, 10 mm separation;
4. CT3 with three EEs, at 10 mm from the reference point, 10 mm separation;
5. CT4 with three EEs, at 5 mm from the reference point, 5 mm separation;
6. CT5, the same as CT1, but the EE moved by 4,5 mm in y-direction;
7. CT6, the same as CT2, but the EEs moved by 4,5 mm in y-direction;
8. CT7, the same as CT3, but the EEs moved by 4,5 mm in y-direction;
9. CT8, the same as CT4, but the EEs moved by 4,5 mm in y-direction;
10. CT9, the same as CT1, but the EE grounded;
11. CT10, the same as CT2, but the EEs grounded;
12. CT11, the same as CT3, but the EEs grounded;
13. CT12, the same as CT4, but the EEs grounded;
14. CT13, the same as CT1, but the EE grounded;
15. CT14, the same as CT2, but the EEs grounded;
16. CT15, the same as CT3, but the EEs grounded;
17. CT16, the same as CT4, but the EEs grounded;
18. CT17, without the EEs, stress relieving with the stress relief pad and metal cone;
19. CT18, closed outer semi conducting screen, stress relieving with the stress relief pad;
20. CT19, closed outer semi conducting screen, without the stress relief pad.

5.1 Effect of grounding the EEs

The constructions of the HS CT both with the EEs at floating potential and grounded were explored and compared to the reference CT. The results for the voltage distribution, total electric field magnitude and tangential electric field component along the path [(0;5.5), (280;5.5)] are shown in Figs. 7, 8 and 9.

5.2 Effect of moving the EEs along r cable axis

Every EE may be viewed as a small toroid, made of semi conducting rubber, incorporated into rubber insulation, with a cross section of a rounded rectangle 10×2 mm. Internal diameter of every EE was initially 28 mm and equal the diameter measured over the stress relief pad. In the next step it was increased by

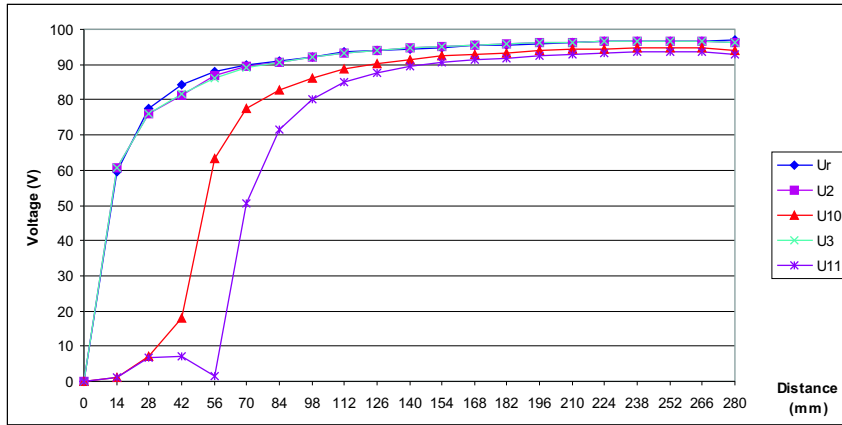


Fig. 7. Voltage distribution for the terminations CTr, CT2, CT10, CT3 and CT11.

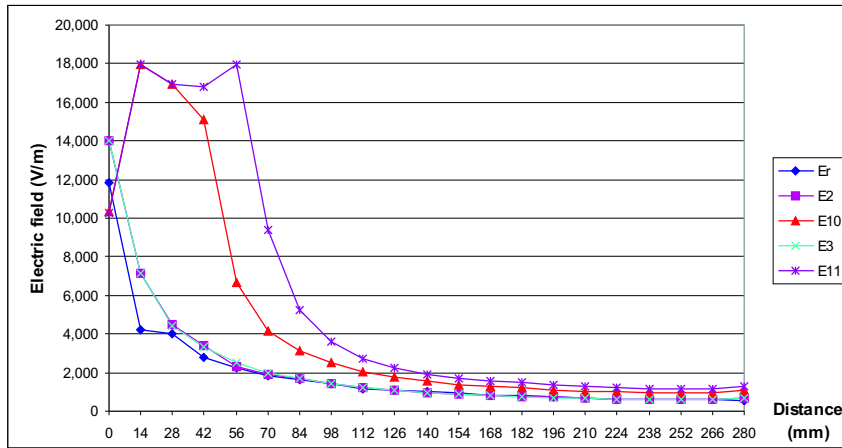


Fig. 8. Electric field magnitude for the terminations CTr, CT2, CT10, CT3 and CT11.

9 mm (37 mm total), which was equal the diameter measured over the DW HST. Corresponding CT constructions were explored and compared to reference CT. The results for the calculated voltage distribution, total electric field magnitude and tangential electric field along the path [(0;5.5), (280;5.5)] are presented in a form of graphs in Figs. 10, 11 and 12.

5.3 Effect of increasing the number of EEs

The number of EEs was increased from 1 to 3 in axial direction keeping the same separation of 10 mm. The results are presented in Figs. 13, 14 and 15.

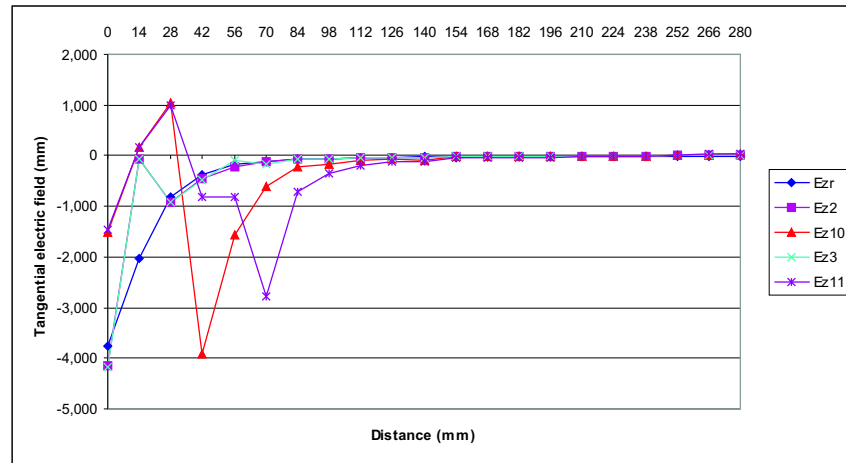


Fig. 9. Tangential electric field for the terminations CT_{Tr}, CT₂, CT₁₀, CT₃ and CT₁₁.

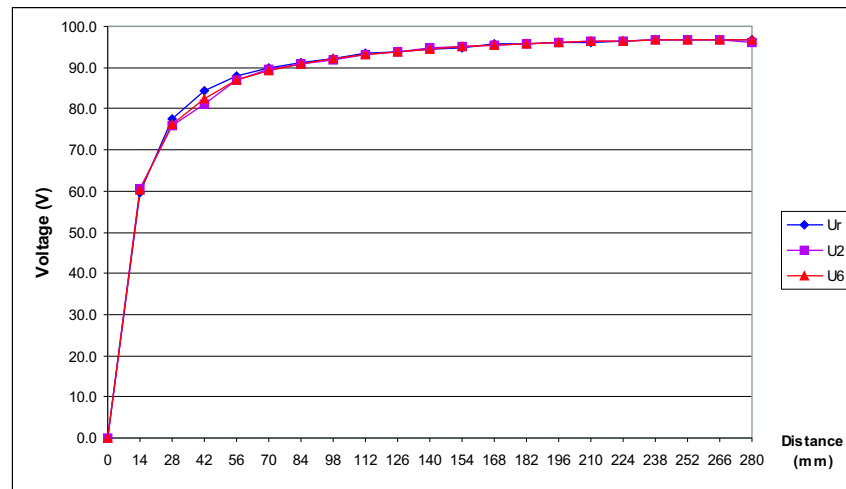


Fig. 10. Voltage distribution for the terminations CT_{Tr}, CT₂ and CT₆.

5.4 Effect of decreasing the separation between the EEs

The initial separation of 10 mm between EEs was decreased to 5 mm. The results are presented in Figs. 16, 17 and 18.

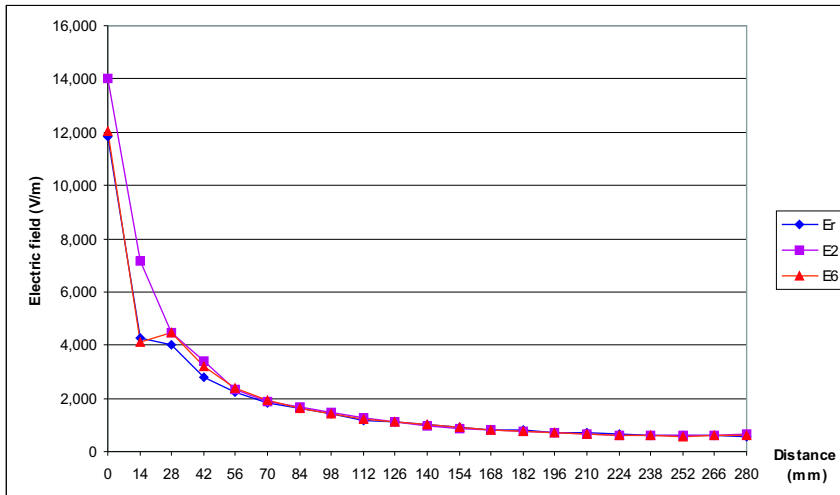


Fig. 11. Electric field magnitude for the terminations CT1, CT2 and CT6.

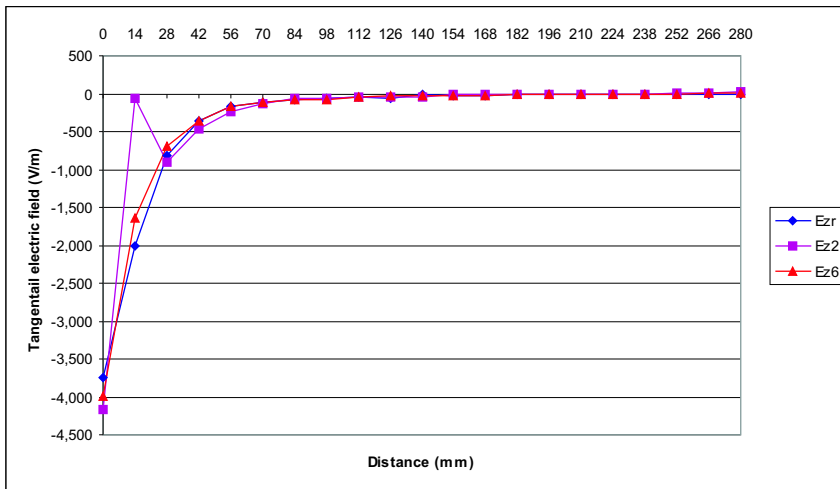


Fig. 12. Tangential electric field distribution for the terminations CT1, CT2 and CT6.

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

As discussed in Section 2.3, a higher number of the EEs, repeatedly placed along the x -axis of the CT, can be viewed as a dashed line in a 2D model. In the case when the separation between the EEs becomes smaller, this line can be approximated with a solid line, i.e. the system of the EEs converges to a cylinder or a cone. That means that electric field in the designs CT17 and CT18 is controlled both geometrically

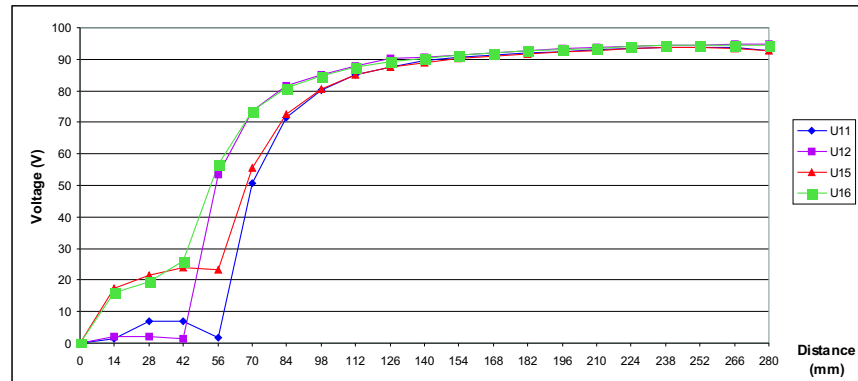


Fig. 13. Voltage distribution for the terminations CT11, CT12, CT15 and CT16.

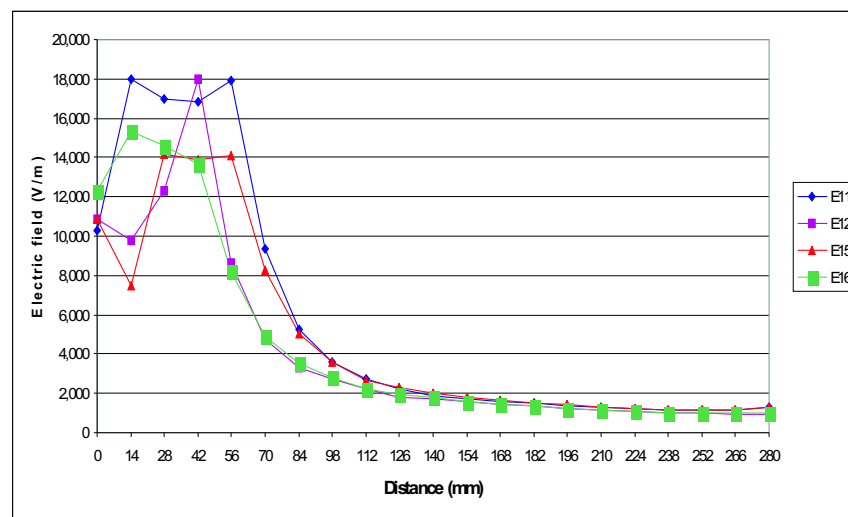


Fig. 14. Electric field magnitude for the terminations CT11, CT12, CT15 and CT16.

and resistively. The construction CT19 was derived from the CT18, but without stress relief pad and with a smaller internal diameter of the outer semi conducting screen (Fig.6). The results of numerical calculation are presented in Figs. 19, 20 and 21.

6 Conclusions

The influences of the EEs and other geometric and dielectric properties on the CT quality were confirmed by numerical calculations as follows:

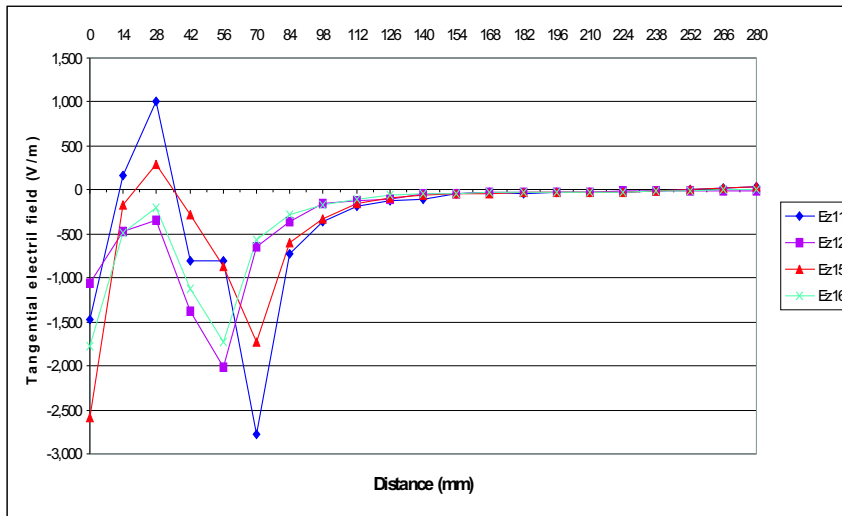


Fig. 15. Tangential electric field for the terminations CT11, CT12, CT15 and CT16.

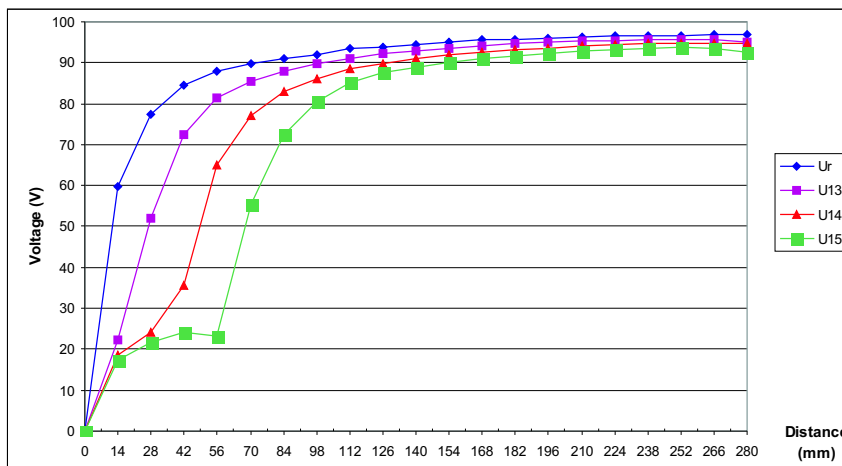


Fig. 16. Voltage distribution for the terminations CTr, CT13, C14 and CT15.

1. All explored terminations were found to be of a reasonable quality, regarding the total electric field magnitude;
2. The terminations CT1, CT4, CT7 and CT8 were not found adequate regarding the tangential electric field magnitude and should be rejected;
3. Tangential electric field magnitudes in the terminations CT2, CT3 and CT5 were found to be close to the critical value, but still acceptable;

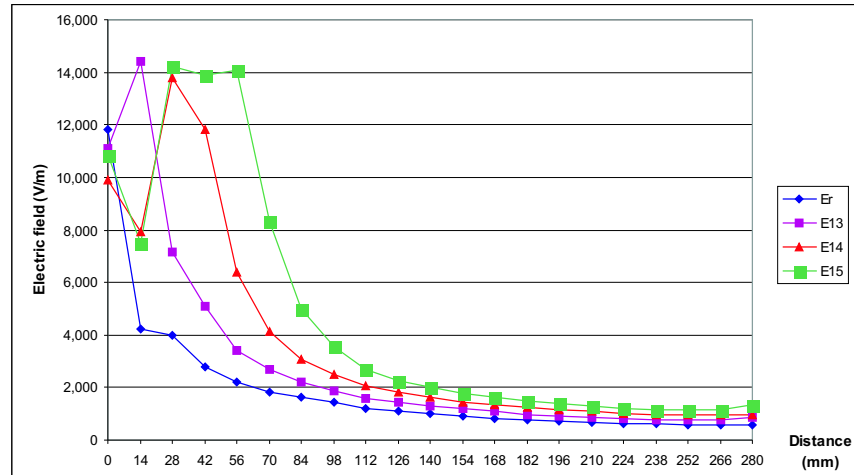


Fig. 17. Electric field magnitude for the terminations CTr, CT13, C14 and CT15.

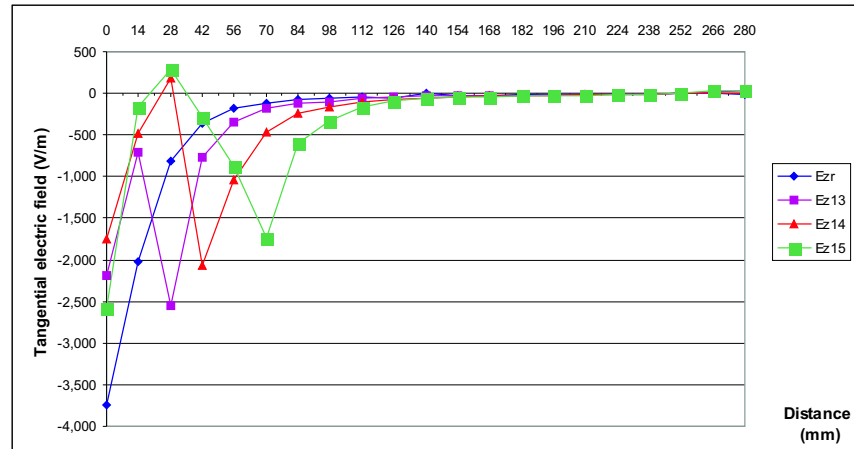


Fig. 18. Tangential electric field for the terminations CTr, CT13, C14 and CT15.

4. All EEs considered, both at the floating potential and grounded ones, strongly affected the electric field, increasing it locally, but not over the permissible values given by [2]. Voltage, electric field and tangential electric field component distribution curves have shown the same gradient, compared to the reference design, but in the different position along the observed contour.
5. Better performances were achieved when the EEs were positioned over the DW HST (greater radius r).
6. More EEs generally decreased only the tangential electric field component.

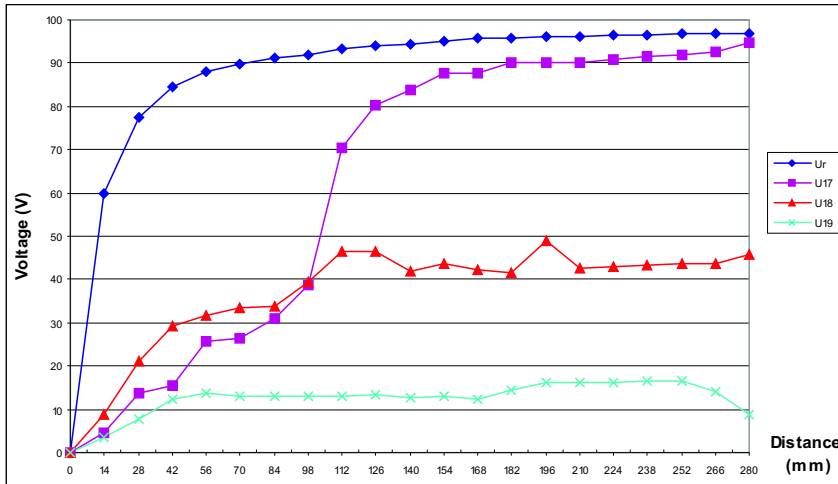


Fig. 19. Voltage distribution for the terminations CT17, CT18 and CT19.

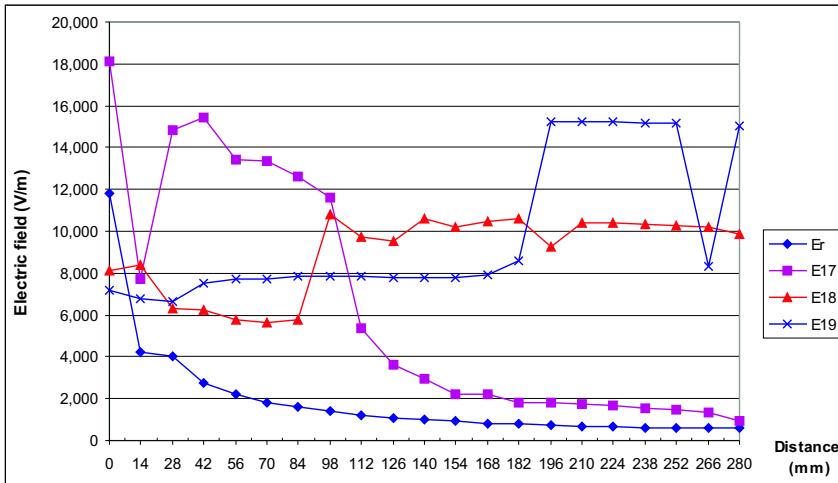


Fig. 20. Electric field magnitude for the terminations CT17, CT18 and CT19.

Local increase of the electric field magnitudes was recorded in the zones around the EEs.

7. Better performances were achieved when the EEs were placed closer to each other.
8. The best technical solution, regarding the electric field magnitudes and the voltage distribution was achieved with the CT19 construction. Such termi-

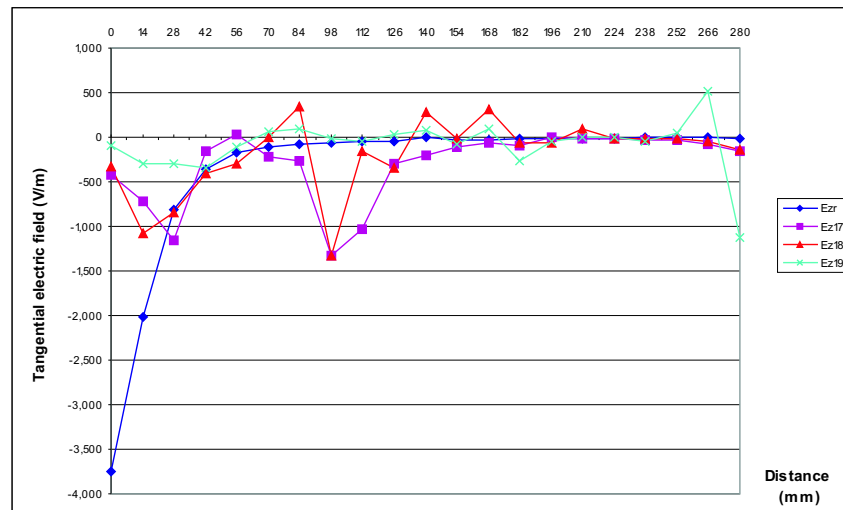


Fig. 21. Tangential electric field distribution for the terminations CT_r, CT₁₇, CT₁₈ and CT₁₉.

nation would allow that three single core terminations, belonging to three different phases, can be placed very close to each other, which may be of high importance for small rooms. Also, due to a very small tangential electric field component, the length of the CT can be shortened to get a very compact design, suitable for connection to transformers, switchgears, motors and other equipment. In the case of outdoor terminations, this concept neednt apply.

9. Based on the results above, it seems, that application of semi conductive EEs, is not justified for the analyzed constructions. For our future investigation, the solutions should be explored for the different non-conductive materials and shapes.

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