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A Study of a MV Cable Joint

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Abstract: Construction parameters of a medium voltage (MV) cable joint were examined in order to reduce the electric field magnitude inside the joint. The joint was covered with a heat shrinkable tube made of two or three layers. The permittivity of the layers was varied. The termination angle of the cable dielectric was also considered.

Keywords: Electric field reduction, Dielectric properties.

1 Introduction

Cross linked polyethylene (XLPE) cables have been in widespread use for decades. Manufactured cable lengths are typically below 1000 m, so several sections of cable may be needed to create a long distance cable line. Consequently, the line quality depends strongly on the reliability of the cable joints. It depends equally on the quality of terminations, but they are considered elsewhere. More details on the cable considered here are listed in **Table 1**. Numerical modelling of the cable joints offers an elegant way to study the electric and magnetic fields inside them, to identify critical spots, improve design and to reduce manufacturing costs [1]. In order to make a joint, the conductors of two consecutive sections of cable are stripped of insulator and joined together with a copper or aluminium ferrule. Sophisticated multilayer materials may be used to insulate the ferrule and fill in the space left by the missing dielectric. The joint is covered with heat shrinkable tube (HST) for protection. Different cable joints are in use, most often with capacitive/geometric, refractive or resistive control of the electric field inside the joint [2]. Two joints from Fig. 1 are described in this work. They combine geometric and high permittivity regulation of the field. The joints may come partially or entirely prefabricated or may be made on site. Good electrical properties of the cable joints depend on the skill of the technicians who assemble them. The termination angle of the cable dielectric is sometimes made according to their

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individual experience. Factory prefabricated parts are preferred in order to minimize human error as much as possible and to reduce assembling time [3]. Accordingly, the goal of this work was to increase the number of prefabricated parts and to reduce the possibility of individual error.

Table 1
Manufacturing data for the Al/XLPE/PVC *cable* (1×120mm^2, 12/20kV).

Conductor (1)	Cross-section (mm^2)	120
	Material	Copper or Aluminium
	Diameter (mm)	15
Conductor screen	Thickness (mm)	0.5
Cable insulation (2)	Material	XLPE
	Thickness (mm)	5.5
Insulation screen (3)	Thickness (mm)	0.5
Metal screen	Cross section (mm^2)	16
Outer PVC tubing	Thickness (mm)	2
	Outer diameter (mm)	34

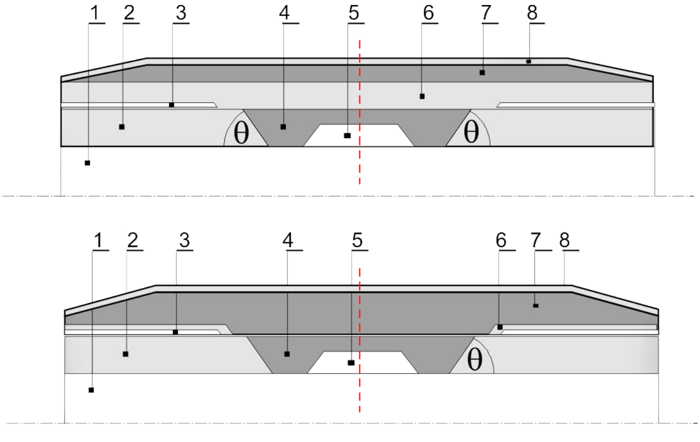


Fig. 1 – *Medium voltage cable joint constructions:* CJ1 - *upper,* CJ2 - *lower.*
Legend: 1 - *conductor,* 2 - *dielectric,* 3 - *cable screen end,* 4 - *ferrule insulation,* 5 - *ferrule,* 6 - *high permittivity layer or wrap* (HPW), 7 - EP *rubber,* 8 - *semiconducting layer.* HST1: 6+7+8. HST2: 7+8.

Table 2
Some data on the joint parts.

Item	Geometry	Relative permittivity, ε_r
Dielectric end (2)	$\theta = 10° - 90°$	2.3
Ferrule (5)	Length 100 mm (70 mm Cu, 133 mm Al), $\phi = 20$ mm	N/A
Ferrule insulation (4)		1-100
High permittivity layer, HPW (6)	1–3 mm thick	10-40
EP Rubber (7)	3 mm thick	3.4
Semiconducting layer (8)	1.5 mm thick	100

Some joint data may be found in **Table 2**. The first type of joint, labelled CJ1, was designed with a three-layer heat shrinkable tube, HST1. The second type of joint, labelled CJ2, was designed with high permittivity wrap, HPW, placed only on top of the cable screen end, under the two-layer heat shrinkable tube, HST2. A range of different values of permittivity were explored for the HPW and for the inner layer of HST1, but in the end both were designed from the same material for ease of comparison.

2 Numerical results

According to our experience [4], cable joints need to be designed with increased permittivity materials and with carefully controlled geometry. Both CJ1, with three-layer heat shrinkable tube HSTl, and CJ2, the lower cost joint with two-layer heat shrinkable tube, from Fig. 1, were considered. The electric field inside the joints was calculated using a commercially available finite element method program. The calculations explored:

1. Permittivity of ferrule insulation, ε_{rf}, (layer 4 from Fig. 1),
2. Angle θ at the boundary between the ferrule insulation and cable insulation,
3. Permittivity ε_{rw} of the bottom layer (layer 6, from Fig. 1) of the HSTl as well as permittivity of the HPW of CJ2,
4. Thickness of layer 6 both for the HSTl and for the HPW of CJ2.

In order to choose the appropriate set of joint parameters, two quantities were calculated:

1. Maximum electric field strength, $E_{\max}$, and
2. Tangential electric field component $E_{\tan}$.

Many calculations were performed in search of the best way to reduce the maximum field magnitude, $E_{\max}$, and if possible at the same time to reduce the tangential component $E_{\tan}$ (magnitude of the electric field vector parallel to the boundary surface). The area affected by the increased field intensity was also assessed.

The relative permittivity, ε_{rf}, of the ferrule insulation was found to play a great role in field formation. In the case of CJ1, a higher permittivity forced the electric field out of the ferrule insulation, so that the highest magnitude of field was compressed in the narrow space inside HSTl. As pointed to by the arrow in Fig. 2, the voltage gradient was very high both at the top of the ferrule insulation and on the upper edge of the cable dielectric. Not shown here, in the case of CJ2, there was a bit more room inside HST2.

The ferrule insulation was made of a rubber-based material with good plasticity. A lower ferrule insulation permittivity, ε_{rf}, between 5 and 10, turned out to be better at reducing the total field. It allowed more room for the field to expand into. The voltage gradient was less abrupt on top of the ferrule insulation (see Fig. 3). The main electric stress was located close to the conductor, at the cable dielectric end, as pointed to by the arrow.

The family of curves in Fig. 4 were calculated for different angles θ, ranging from 10 to 90 degrees. Different angles gave different geometries for the dielectric cone: for $\theta = 90°$ – no dielectric cone around the conductor, for $\theta = 28°$ – 10 mm long cone, for $\theta = 15°$ – 20 mm long cone and for $\theta = 10°$ – 30 mm long cone. Larger θ (shorter cone at the end of the cable insulation) resulted in a lower total field magnitude. Smaller θ (longer cone) was found to reduce the tangential field component along the cable insulation boundary but at the same time significantly increased the maximum total field magnitude inside the joint. Although the tangential field component may be important, the total field magnitude is crucial.

Fig. 4 illustrates how the maximum strength of the total electric field inside joint CJ1 changes as a function of the ferrule insulation relative permittivity. The range 1–100 was explored numerically. As can be seen from Fig. 4, a relative permittivity in the range 5–10 was found to be best for total field reduction. A larger permittivity, $\varepsilon_{rf} = 10$ and more, as in semiconducting or conducting materials, was found to produce an extremely high total field at certain points and thus obstruct the quality of the joint. The idea of having conducting or semiconducting parts in the joint was tested based on some earlier designs of high voltage cables [4]. In this case, for a given geometry, the introduction of additional conducting or semiconducting material did not prove beneficial.

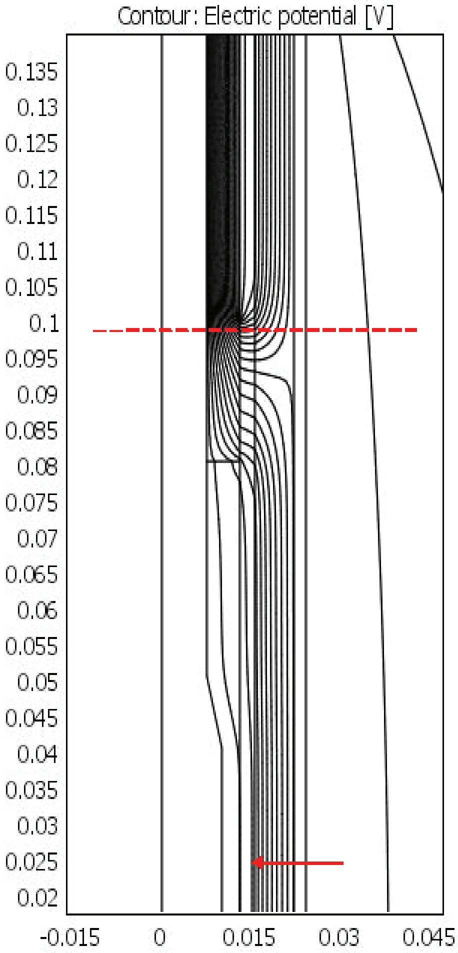


Fig. 2 – *A detail of the calculated voltage of* CJ1-40/90 (*ferrule insulation* $\varepsilon_{rf} = 40$, *cable end boundary angle* $\theta = 90°$).

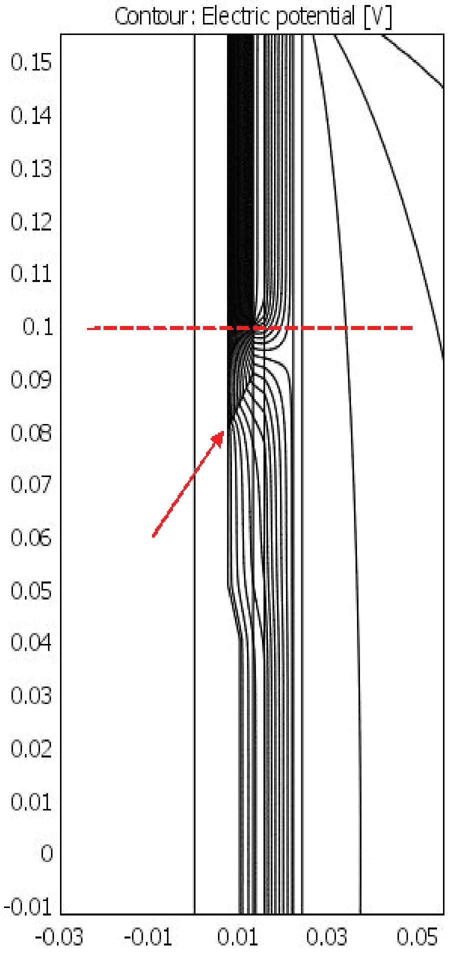


Fig. 3 – *A detail of the calculated voltage of* CJ1-7/28 (*ferrule insulation* $\varepsilon_{rf} = 7$, *cable end boundary angle* $\theta = 28°$).

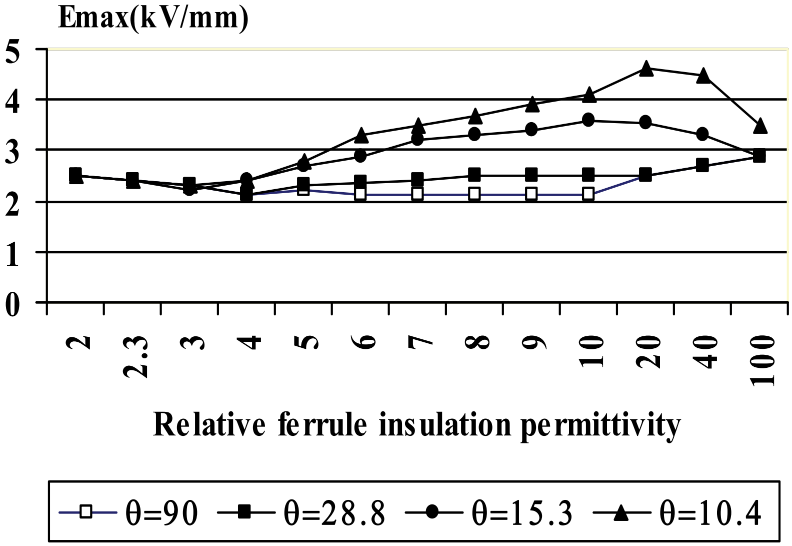
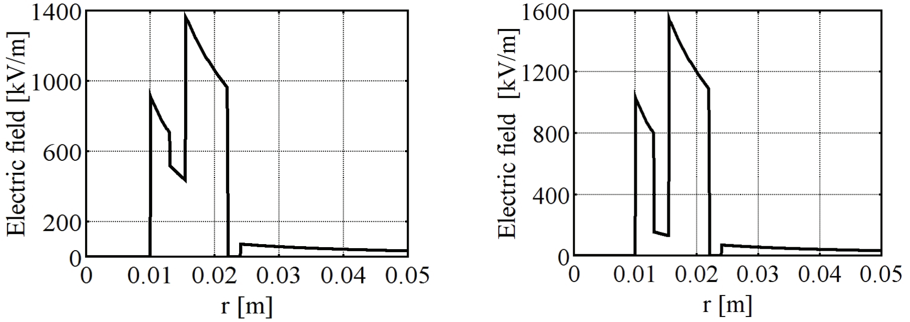


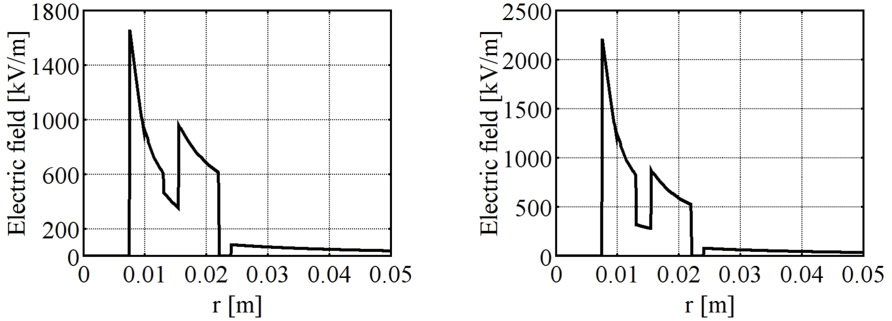
Fig. 4 – *Maximum electric field strength of* CJ, *as a function of ferrule insulation permittivity* ε_{rf}, *and of boundary angle* θ.

Fig. 5 represents the calculated radial and axial change of electric field inside CJ1-7/28. Observe how the field magnitude drops in the high permittivity layers. Both the inner layer of the three-layer HST1 and the HPW of CJ2 were designed from the same material with a relative permittivity $\varepsilon_{rw} = 10$ or $\varepsilon_{rw} = 40$.

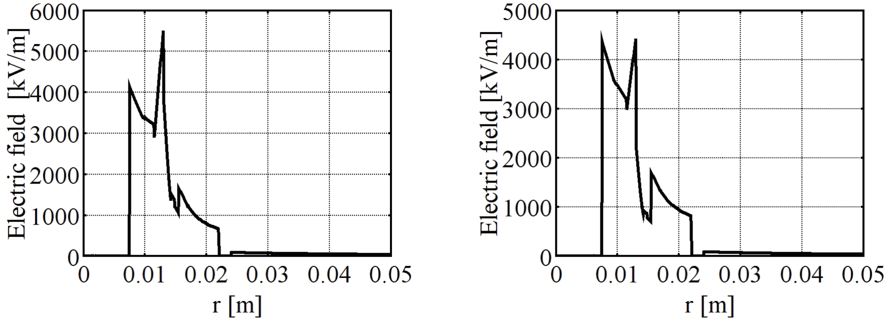
The electric field strength changes both with radial and axial distance from the centre of the joint, as can be observed in Fig. 5. The centre of the joint corresponds to the height $z = 0$. The height $z = 0.08\,\mathrm{m}$ is closer to the cable dielectric end and the height $z = 0.1\,\mathrm{m}$ is closer to the cable screen end. The high permittivity of layer 6, ε_{rw}, pushes the field outside the layer and the maximum total field strength in the neighbourhood goes up. This is one of the main reasons why, to compensate, the ferrule insulation relative permittivity must be kept below 10. At the most critical height, at the cable screen end, the maximum total field strength was calculated as $E_{\max} = 5.28\,\mathrm{MV/m}$, for $\varepsilon_{rw} = 10$, compared to $E_{\max} = 4.83\,\mathrm{MV/m}$, for $\varepsilon_{rw} = 40$ (See Figs. 5a3 and 5b3). The higher permittivity $\varepsilon_{rw} = 40$ seems to work better.



$z = 0$ (a1); $z = 0$ (b1);



$z = 0.08$m (a2); $z = 0.08$m (b2);



$z = 0.1$m (a3); $z = 0.1$m (b3);

Fig. 5 – *The electric field radial profile at different axial distances from the centre of joint* CJ1-7/28, $\varepsilon_{rf} = 7$, $\theta = 28°$; (a) $\varepsilon_{rw} = 10$; (b) $\varepsilon_{rw} = 40$.

It is worth mentioning that a relative permittivity $\varepsilon_{rw} = 40$ simultaneously reduced the tangential component of field in CJ1 to an acceptable value below 500 kV/m: Inside CJ1-7/28, we calculated a maximum tangential component $E_{\tan} = 621\,\text{kV/m}$ for $\varepsilon_{rw} = 10$, compared to a maximum $E_{\tan} = 362\,\text{kV/m}$ for $\varepsilon_{rw} = 40$. The higher permittivity $\varepsilon_{rw} = 40$ seems to fulfil both search criteria. A relative permittivity higher than $\varepsilon_{rw} = 40$ may affect the creep distance and was not considered for safety reasons.

The thickness explored for the HPW was in the range from 1 to 3 mm. The electric field at the cable screen end was well controlled by a 1 mm thick high permittivity bottom layer of HST1, in the case of CJ1. In the case of CJ2, a 1 mm thick HPW was used. A greater thickness was found unnecessary. For electric field regulation at the cable screen end (layer 3 in Fig. 1), a cover with increased permittivity was found essential.

3 Experimental results

According to the calculations, both designs, CJ1 and CJ2 should have similar electrical properties. CJ2 may have 10–20% cheaper parts but it has a longer installation time and offers more opportunity for human error. The price reduction does not seem to justify the effort to assemble CJ2. For this reason, only CJ1 was manufactured and tested experimentally. The total length of the joint was chosen so that the voltage would not damage the insulating material. According to IEC 112, the creep distance for fair conditions should be kept above 16 mm/kV. In our design, tracking between the two consecutive cable screen ends was set to 320 mm for a 20 kV copper cable or to 390 mm for a 20 kV aluminium cable.

Only CJ1 was chosen for experimental studies. The main conclusions from the numerical results - that better joints may be made with moderate permittivity, below 10, for the ferrule insulation and with an angle θ between 28 and 90 degrees, were tested experimentally. Three different samples of CJ1 were prepared for experimental testing. The results of the experimental tests are summarized in **Table 3**.

The first design, labelled CJ1-40/90, was manufactured with an increased ferrule insulation permittivity of $\varepsilon_{rf} = 40$ and with boundary angle $\theta = 90°$ (no cone at the dielectric end). The second, labelled CJ1-7/28, had a lower ferrule insulation permittivity of $\varepsilon_{rf} = 7$ and a boundary angle $\theta = 28.8°$ (10 mm long cone). Both constructions performed well and both passed the tests according to the VDE 0278 standard. CJ1-7/28 performed slightly better in respect of partial discharges, as can be seen from row 11 of **Table 3**. In spite of the good numerical results, an angle $\theta = 90°$ was not considered convenient for joint-making. Perpendicular interfaces make it difficult to install the ferrule insulation. Because of this, joints with small cones up to 10 mm in length (θ between 28 and 90 degrees) were considered to be better adapted to fabrication.

Table 3

The performance tests results according to VDE 0278.
Legend: CJ1-40/90 (*ferrule insulation permittivity* $\varepsilon_{rf} = 40$ *and* $\theta = 90°$),
CJ1-7/28 (*ferrule insulation permittivity* $\varepsilon_{rf} = 7$ *and* $\theta = 28°$).

No.	Item	Test voltage (kV)	CJ1-40/90	CJ1-7/28
1.	AC 50Hz, 1 min	55	Passed	Passed
2.	Partial discharges	24	0 pC	0 pC
3.	Impulse voltage (10 positive, 10 negative, 1.2/50 μS)	125	Passed	Passed
4.	Current cycling (5+3 hours, cond. temp. 95°C 3 cycles)	30	Passed	Passed
5.	Partial discharges	24	0 pC	0 pC
6.	Current cycling (5+3 hours, cond. temp. 95°C 60 cycles)	30	Passed	Passed
7.	Partial discharges	24	4 pC	0 pC
8.	Current overload 1 sec. 250°C		Passed	Passed
9.	Partial discharges	24	10 pC	4 pC
10.	Current cycling (5+3hours, cond. temp. 95°C, 63 cycles)	30	Passed	Passed
11.	Partial discharges	24	20 pC	10 pC
12.	DC voltage 30 min	96	Passed	Passed
13.	AC voltage	50 60	5 min 30s*	5 min 30s*

*Flashover at cable termination

The third manufactured cable joint, labelled CJl-100/28, with semi-conducting material on top of the ferrule, of relative permittivity $\varepsilon_{rf} = 100$ and boundary angle $\theta = 28.8°$ (10 mm long cone), did not pass the test. Such an outcome confirmed the numerical prediction that the ferrule insulation must not be replaced by semiconducting material.

4 Conclusion

There are many solutions for MV cable joints. Our efforts were directed at improving the design, based on numerical calculations and on site experience. The main goal of this study was to reduce the maximum field strength, $E_{\max}$, and tangential component, $E_{\tan}$, parallel to the boundary surfaces, as much as possible, thus protecting the cable joint from accelerated aging.

Two parameters were monitored in order to choose the best joint design:

1. Total electric field strength and
2. Tangential field components along boundaries.

Two similar cable constructions were explored. The first type, CJ1, incorporated a three-layer heat shrinkable tube, HST1. The second type incorporated a two-layer heat shrinkable tube, HST2, on top of the HPW. The electric field magnitude inside the joints was calculated by the finite element method. The calculations showed that:

The maximum electric field strength in the joint is affected a great deal by the permittivity of the ferrule insulation, ε_{rf}.

- A relative permittivity of the ferrule insulation, ε_{rf}, between 5 and 10 was found to be the most suitable. Materials with higher permittivity must not be used.
- The angle between the ferrule insulation and cable insulation, θ, affects the peak magnitudes of both the total field and tangential components of field along the boundary surfaces. These demands oppose each other. A smaller θ was able to reduce the tangential components but at the same time it increased the total field magnitude, which was not permissible.
- An angle θ in the range 28–90° was found to be acceptable. A larger θ is better in theory, but not practical in reality.
- High permittivity of the HST1 inner layer, in the case of CJ1, as well as of the HPW, in the case of CJ2, ε_{rw}, was essential in order to reduce the field magnitude at the cable screen end. A value $\varepsilon_{rw} = 40$ was found to be suitable.
- Increased thickness of either the inner layer of the HST1 or of the HPW, in the case of CJ2, did not affect the field to any large extent. A thickness of 1 mm was found to be appropriate.

Besides this, the cable insulation should be left intact as much as possible; a longer insulation cone results in a larger contact surface that has to be additionally treated on site with sandpaper and lubricated with silicon oil. A larger contact surface may also cause more micro discharges.

As a result of this work, a cutting tool can be designed for on site preparation of an optimally shaped dielectric cone. All other parts of the joint labelled CJ1, including ferrule, ferrule insulator and three-layer HST1, can be factory prefabricated.

Future work should employ a genetic algorithm-based search or some other optimization technique for the best possible joint design.

5 Acknowledgement

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