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Lightning strikes to ground affecting underground power cables

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SUMMARY

The possible danger to underground power cables from atmospheric lightning strikes close to the cable route has not been discussed very much in the past. Since most of the underground power cable routes are in the range of 10 km length or below the likelihood of a lightning strike close to the cable route is small, especially in temperate climate zones where the number of thunderstorms is limited. In addition, many underground high-voltage cables are installed in urban areas where buildings can act as shielding structures against lightning strikes. But this situation may change now.
The industry sees the planning and implementation of very large underground cable interconnectors where the route length may reach several hundreds of kilometers. As a matter of statistics, the number of expected lightning strikes close to the cable route will become substantially larger. The sheer length of the new interconnectors often requires the routing to pass rural areas and the green field where the lightning strikes are not distracted by large buildings.
A lightning strike into ground close to the cable can result in multiple cable sheath punctures but does not necessarily cause a breakdown of the main insulation. The cable may remain in service and the damage may go undetected for weeks, months or even years. However, the ingress of water may deteriorate the main insulation and cause a full breakdown later.
Since the reliability and availability of these interconnectors often are key for the security of power supply the planner and operator of such interconnector needs to consider the risk of direct lightning strikes and suitable measures to mitigate risks.
This paper explains the phenomenon of lightning strikes close to power cable installations and their consequences. It is shown how the risk level can be estimated with regards to the location of the cable installation and how this risk level can impact on the availability of the asset.
Possible protection measures like shield wires are shortly evaluated.

KEYWORDS

Underground cables, long interconnector, lightning strikes, direct strike into soil, sheath damage, availability, shield wires.

1. INTRODUCTION

Powerful UHV underground transmission cable systems have been installed in the recent years and this trend will increase to very large projects in the future for bulk transport of electric power between and across the countries. In case of an outage of such a cable system the load cannot be re-routed easily through the remaining power grid. The availability of these cable systems is an important economical factor for the cable operators since outages of these cables may render substantial loss of income.

Cable asset managers are studying failure statistics carefully in order to assess the economic risks associated with the operation of the link. Probably the most comprehensive summary of operational experience with UHV cables has been published by Cigre [1]. The failure causes are usually subdivided in internal, external and unknown. Human interference such as the notorious “excavator” is made accountable for “external failures”.

Recently, a possible non-human cause of external failures has been identified: the risk of cable damage by thunderstorm strikes which hit the earth close to the underground cable system.

Initiated by a real cable damage case we investigated the potential distribution in the soil subsequent to a strike impact and how this can damage the cable system. A moderate strike direct into the soil can damage the underground cable from several meters distance. At first glance the probability for such an event seems to be low. However, increasing cable route length will increase the probability that the cable system is struck somewhere. For cable routes of several hundreds of kilometres there is a serious threat to the availability of the cable system.

The most intuitive countermeasure would be the installation of bare shield wires running above the cable system. We were able to demonstrate the usefulness of shield wires.

2. OBSERVATION FROM THE FIELD

Although the threat to underground cables has been described decades ago only few cases of power cable damages related to direct strike impact have been reported [2] [3]. In a group of directly buried high-voltage underground cables we have discovered multiple cable sheath damages in several cables within a 20 m portion of the cable route [2]. The cables were directly buried in a rural area. Some of the damages were barely visible pinholes while others included severe burning of the sheath, metal foil and screen wires (Figure 1). Water ingress was also found. However, the main insulation was undamaged.

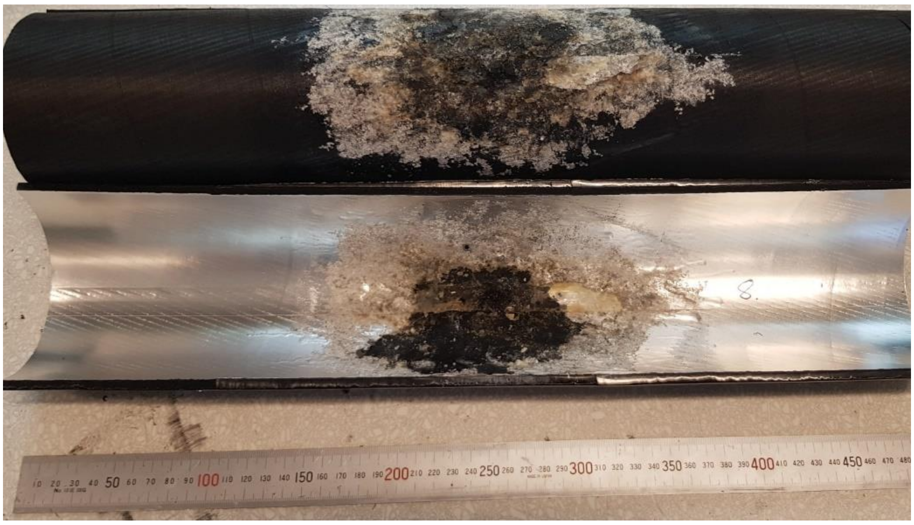
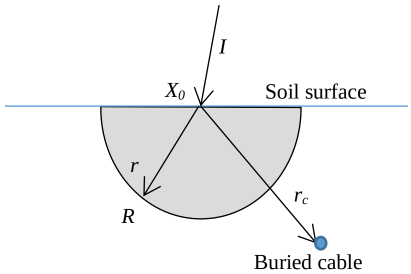


Figure 1 Burned aluminium laminate

The elapsed time between the formation of the damages and their discovery could not be established. No anthropogenic external aggression (excavator, construction etc.) could be found near the damages. The fact that multiple cables at the same spot were affected indicated that they were damaged by the same localised root cause. The only feasible explanation was an impact of an atmospheric strike into the ground close to the cables. A single atmospheric strike has the ability to branch into multiple separated impacts into ground [6] which can explain the observation of multiple damages.
Statistics from the national meteorological institute showed that strike frequencies were exceptionally high in two years between installation of the cable system and the discovery of the damages. The sheath damages found in this location had not led to a breakdown of the main insulation.

3. THE HEMISPHERICAL MODEL

Widely accepted theories on the electrical processes in the soil after an atmospheric strike have not been found. But already the straightforward hemispheric model used in this paper reveals good insight into the matter [2] [3]. Based on the understanding of the behaviour of earthing electrodes it postulates that the injection of the strike current into the soil creates a hemispherical potential field centred on the impact point X_0.



The voltage at point R is given by:

$$U(r) = \frac{I \cdot \rho_s}{2\pi r} \qquad \text{Equ. 1}$$

where r is the radial distance of any point R from the strike position X_0. I is the strike current and ρ_s the uniform electrical resistivity of the soil. The situation was also modelled in a FEM software confirming the validity of Equ. 1 under the conditions of uniform soil properties and the absence of arcing within the soil.
The surface of the cable is exposed to a voltage according to Equ. 1 while the cable screen is at the potential of the undisturbed earth. Fig. 2 shows the situation with the red line indication the high potential on the cable surface.

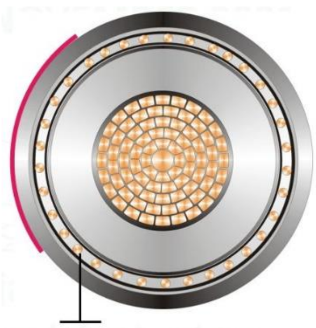


Figure 2 Potential difference over the outer cable sheath

If the potential on the cable surface exceeds the impulse breakdown strength of the sheath a breakdown can be expected. The impulse breakdown strength of the sheath is ≈ 50 kV/mm [2] [3]. Knowing the impulse breakdown strength of the cable sheath a critical distance r_c can be calculated for each strike current magnitude I and soil resistivity ρ_s. If the strike occurs within the critical distance r_c a sheath breakdown can be expected.
The hemispherical model must be understood as a first approach simplification. The resulting electric field strength in the soil, especially for strikes with high magnitude, exceeds the breakdown strength of the soil which is in the range of 1…2 kV/mm [5]. This will cause arcing phenomena in the soil which are difficult to model.

4. STATISTICAL CONSIDERATIONS

Cable system planners need to know the expected unavailability of the cable system caused by direct strike impacts in order to design suitable countermeasures, or even relocate exposed parts of the cable route.
A statistical approach has been presented in [2], starting with the number of strikes per year and area unit.

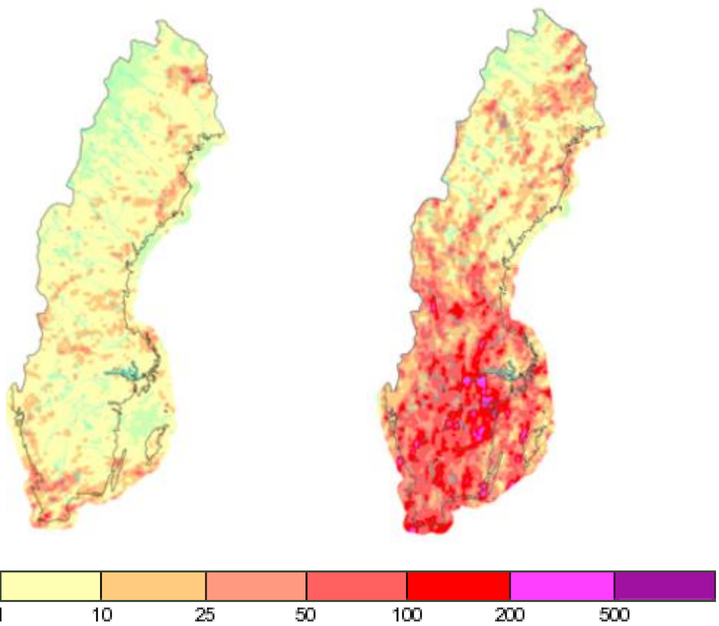


Figure 3 Number of strikes in Sweden 2017 (left) and 2019 (right), per 100 km²

Figure 3 shows the total number of strikes per year and area unit in different areas of Sweden [4]. It becomes visible that the strike frequency can vary substantially between different locations and between years.
Next, we try to find out the probability $P(I)$ of a strike magnitude to exceed the current I [1]:

$$P(I) = \frac{1}{1 + (I/31)^{2.6}} \qquad \text{Equ. 2}$$

where the unit for I is kA. For each current magnitude the critical distance r_c defines a risk corridor along the cable route where a strike within the corridor puts the cable in danger.

Combining this with the cable route length and the number of strikes per year and per km^2 the number of potentially dangerous strikes along the cable route, added over all strike magnitudes, can be calculated.
It has been calculated that for an assumed strike frequency of 1 strike/yr.km^2 the number of potentially dangerous strikes N can be as high as N=2.4 possibly dangerous strikes per year for a cable route of 100 km and a soil resistivity of ρ_s = 500 Ωm [2].
A sheath damage caused by a lightning strike does not necessarily lead to a main insulation breakdown. However, a single strike can develop several damages at the same time. We do not know how many of these damages eventually might cause a breakdown of the main insulation. The resulting number of N=2.4 strikes per year is depending on several assumptions. However, the number can serve as a benchmark to investigate the influence of several parameters on the number of potentially dangerous strikes.
The statistical risk assessment as outlined above is based on a cable installation in a flat uniform landscape. This situation can be found in the green field. Buildings nearby the cable route reduce the risk of strikes hitting the ground [7].

5. FINITE ELEMENT MODEL

The FEM calculation has been performed in 3D [8]. The model consists of a soil box with a pair of cables installed in horizontal direction along the x-axis (Figure 4). Two filaments close to the upper surface represent a pair of cables A single dot is added to the top surface to simulate the lightning strike position. To optimise the computation time, the model is built using an infinite element domain at the sides and bottom of the ground box. This feature scales the elements in one direction so that 1 m distance in this area represents e.g. 100 m in reality. This enables the model to consider a large surrounding without an extremely large mesh.
The boundary conditions of the model are:

- A lightning current I imposed at the point at the top of soil
- Grounding at the cable screen at the far end
- Grounding at the bottom of the soil box.

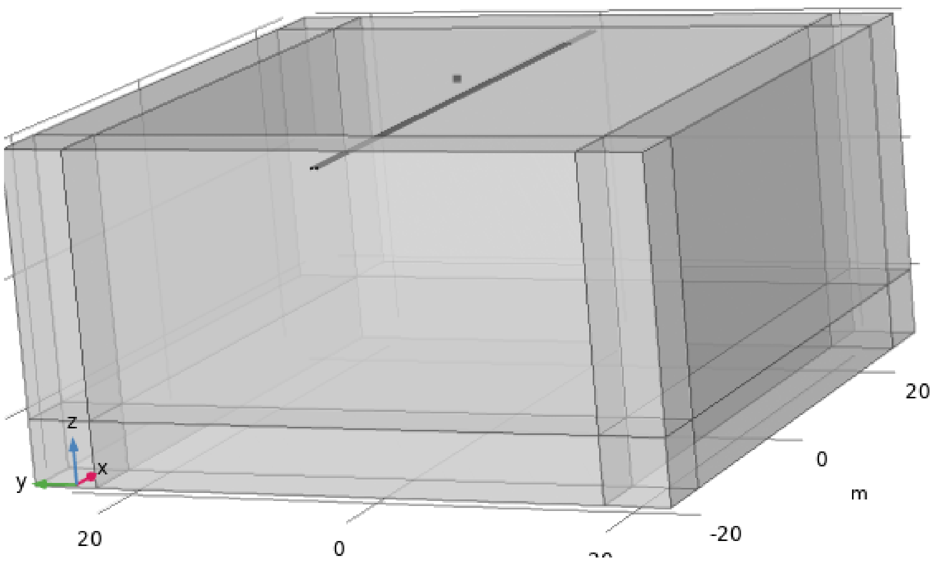


Figure 4 FEM simulation box. Explanations in the text.

6. VERIFICATION FEM MODEL

To verify the performance of the FEM simulations a benchmark is first made against the hemispherical method described earlier. The example considers a single cable installed at 1.2 m burial depth and with a soil resistivity of ρ_s = 500 Ωm.
As in the hemispherical model described above the verification starts with finding out at which maximum lateral distance from the cable a strike can cause an electric stress in the cable sheath exceeding 50 kV/mm (breakdown condition). This defines again the width of the risk corridor for a particular strike magnitude. Also, for each strike magnitude the number of potentially dangerous strikes can be calculated. Figure 5 indicates the number of potentially dangerous strikes in the 100 km cable route as a function of strike magnitude for each interval of 5 kA. The total strike frequency is assumed to be 1 strike/km^2·yr. The total number of potentially dangerous strikes in the cable route is the sum of all columns in the diagram. In our FEM calculation example, the result is 2.36 expected strikes/year which matches the result from the hemispherical model.

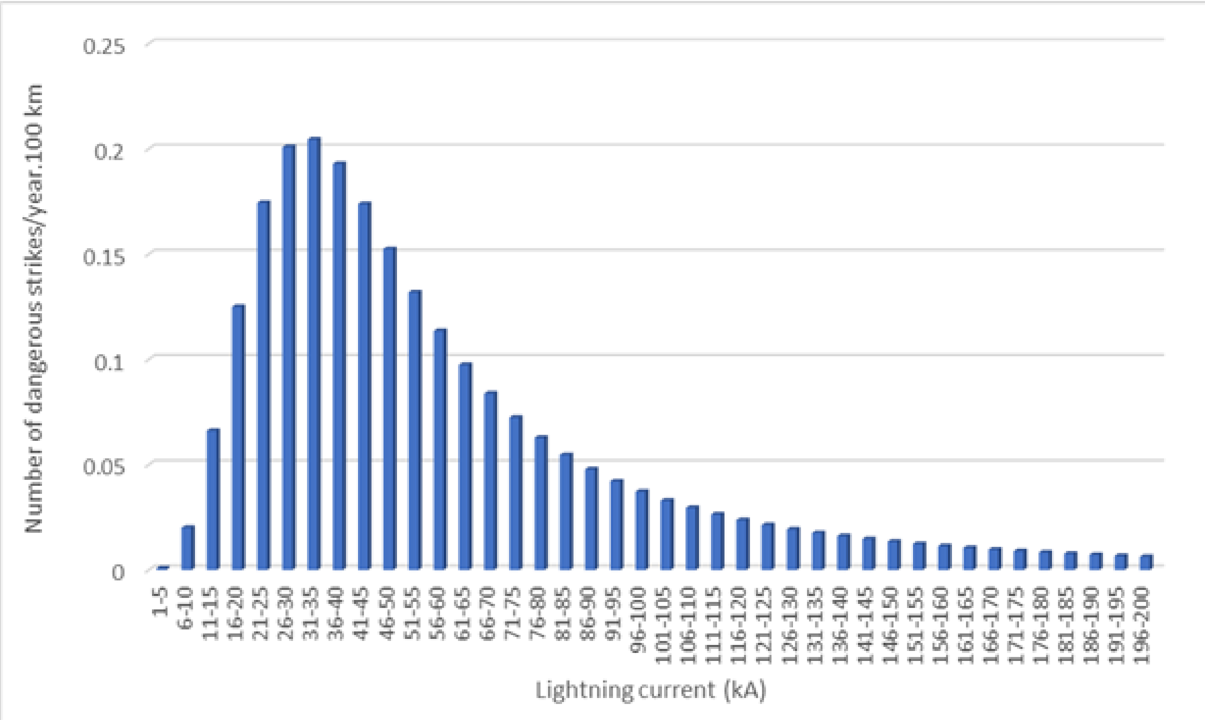


Figure 5. Number of potentially dangerous strikes in the 100 km cable route as a function of the lightning current, calculated for 5 kA intervals.

The good agreement of the FEM simulation result with the result from the hemispherical approach allows us to calculate the impact of different installation parameters which cannot be done with the analytical formulas, such as backfilling, ducts or shield wires. This will be further discussed in the coming chapters.

7. INFLUENCE OF CABLE DESIGN PARAMETERS

The design parameters of the cable seem not to have any influence on the resilience of the cable system except one: the dielectric strength of the outer sheath. According to the simplified hemispherical model the number of potentially dangerous strikes is inversely proportional to the dielectric strength of the sheath. Increasing the sheath thickness from 5 to

6 mm would reduce the strike damage number by approx. 17%, all other parameters kept the same.
Conductor size, insulation material and thickness are not expected to have any influence.

8. INFLUENCE OF INSTALLATION PARAMETERS

The width of the risk corridor is determined by the critical distance between the hit point of the strike to the position of the cable. An example is demonstrated in [2] where the risk corridor for a 18-20 kA strike is 11 m wide. Under such conditions a change of the burial depth, e.g from 1.5 m to 2 m, would not make a large difference (see Figure 6).

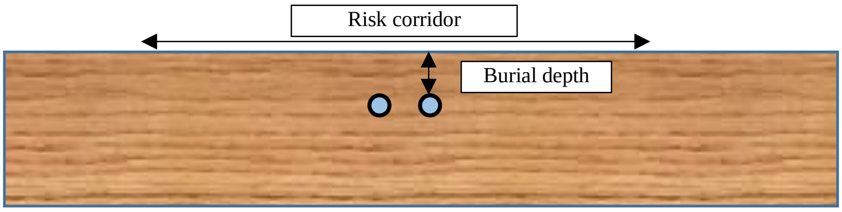


Figure 6 Relation between burial depth and width of risk corridor

The electrical resistivity of the soil plays the largest role of all installation parameters. In most cases buried cable systems are installed with defined backfill material to create certain thermal conditions. The electric properties of the backfill material are, however, less important than the properties of the native soil surrounding the cable trench. In the right part of Figure 7 the cables are laid in a box of back-fill material with $\rho_{backfilll}$ = 50 Ωm in a surrounding with ρ_s = 500 Ωm. This measure reduces the electric potential on the cable surface from 588 kV (without special backfill) to 474 kV, a reduction of 19 %.
This also reduces the complete likelihood for damages from the earlier stated 2.4 cases per 100 km cable to 2.3 cases.

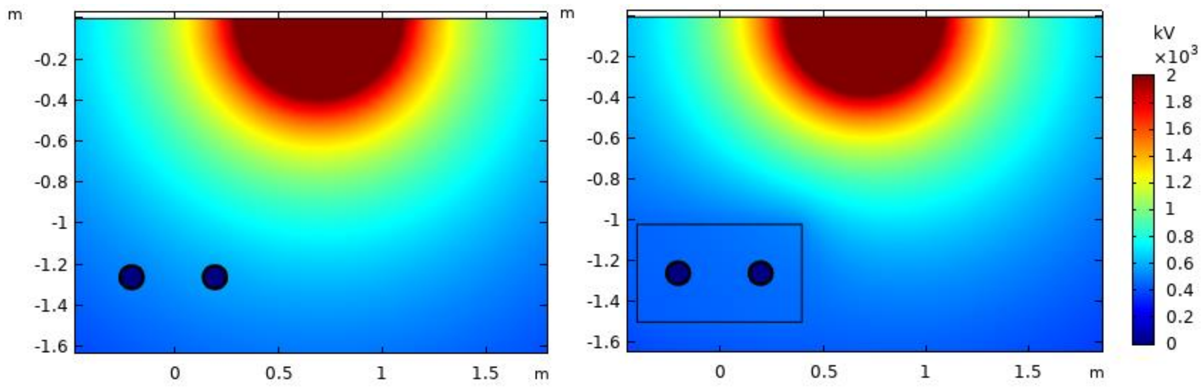


Figure 7. Comparation of lightning strike above the cable with I=10 kA for (left) complete soil with ρ_s = 500 Ωm and (right) soil with ρ_s = 500 Ωm and a backfill around the cable with $\rho_{backfilll}$ = 50 Ωm

9. PIPE DUCTS

The situation becomes more complicated if the cable system is installed in PE or PVC conduits. The position of the cable inside the duct pipe is not predictable. In most places the cable is touching the inside of the duct pipe creating small gaps of air next to the touch point.

The arising electric field distribution is shown in Figure 8. The uniformity of the electric field in the cable sheath ≈ 35 kV/mm is caused by the semiconductive skin on the outside of the cable. This value can be tolerated in an undamaged sheath. However, the electric field in the duct material at the touch point (> 75 kV/mm) exceeds the breakdown strength. Also, the electric field in the air gap next to the touch point is much higher than the dielectric strength of air (≈ 3 kV/mm). Most probably, a breakdown in the air will be initiated and might eventually lead to a breakdown in the duct material. However, the transient character of the lightning impulse might create different field distributions and breakdown mechanisms.

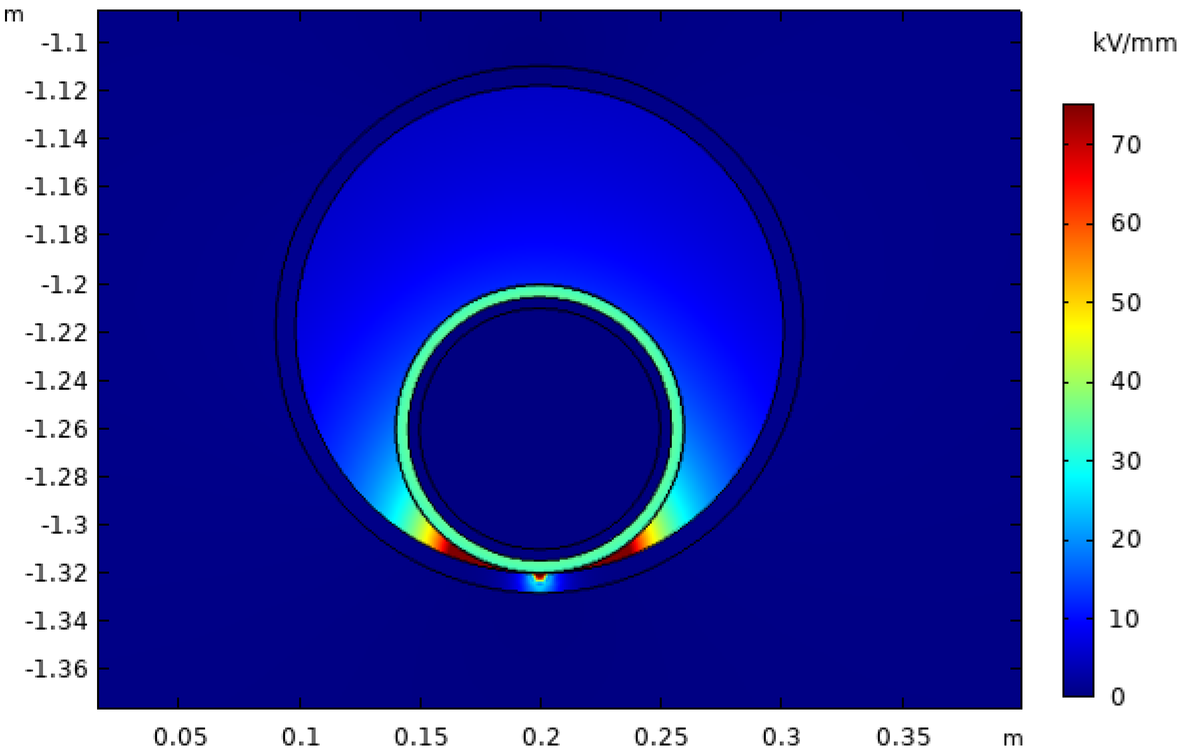


Figure 8. Electric stress for cable in duct

The color mapping of Figure 8 is capped to 75 kV/mm in order to visualize even moderate field strength values. Higher values than 75 kV/mm appear in the air gap and in the duct wall at the touching point.
An experimental approach of this situation would be valuable.
A steel pipe duct would change the situation completely. A steel pipe would provide a conducting envelope around the cable with the ability to carry away parts of the impinging lightning strike current. The length resistance of the steel pipes and their contact resistance to earth are factors probably important for the protective effect of steel pipes.

10. COUNTERMEASURES

The installation of shield (guard) wires to protect buried cables is known from the telecom cable industry [7]. The main idea in this application is to distribute the strike current between the shield wires and reduce the current magnitude in the metallic parts of the telecom cable. In the case of underground power cables however, the main goal is to protect the cable sheath from penetration.

Finite Element Methods (FEM) have been used to calculate the possible benefits of shield wires.

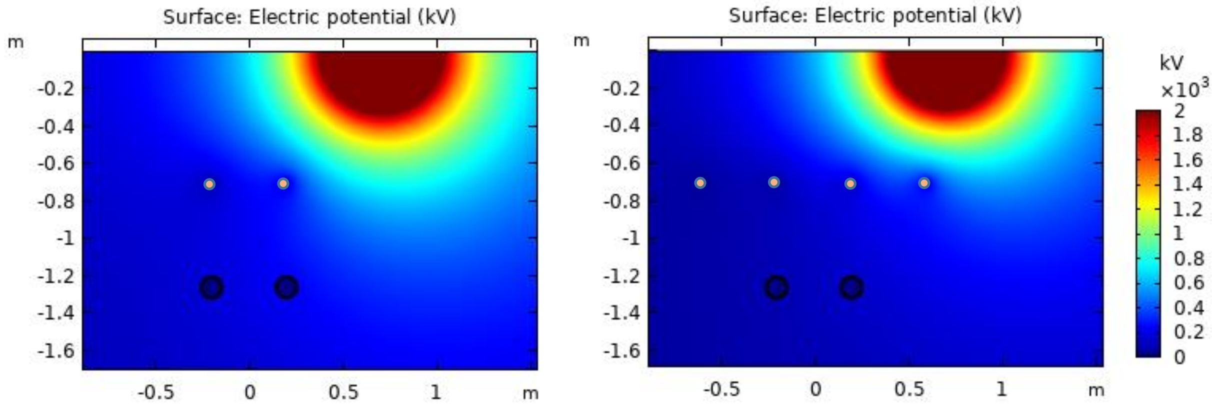


Figure 9 Potential distribution in the soil with two (left) and four (right) shield wires

Figure 9, left, shows the same cable system as Figure 7 but with one shield wire above each of the two power cables. The right part of Figure 9 shows the same cable system with in total four shield wires which reduces the potential at the cable sheath further. By this, the number of potentially dangerous strikes will be reduced accordingly.
The statical analysis has then been repeated for lightning currents between 1 to 200 kA and the expected number of dangerous strikes per 100 km for the example case with ρ_S = 500 Ωm has been calculated. Having two shield wires the number of dangerous strikes is 0.83 per 100 km of cable and year while a system with four shield wires will experience 0.51 cases per 100 km of cable and year. Compared to the case without shield wires the risk has been reduced by 65% and 78% for 2 and 4 shield wires, respectively.
It must be mentioned here that few shield wires can reduce the risk for cable damage but cannot eliminate the risk completely.
Other metallic elements such as pipes, meshes, shells, sheets, etc, are also expected to be useful to protect the cable system.

11. CONCLUSION

In long underground cable transmission lines the risk for sheath damages by direct strike hit into the ground cannot be neglected. Depending on the soil resistivity and the local strike frequency, the number of possibly dangerous strikes can amount to inacceptable levels. A risk assessment in a particular case would take into account the variation of soil resistivity and strike frequency along the cable route.
A change in the cable sheath thickness can reduce the risk only by a small amount.
The risk of strike-induced unavailability of the cable system may justify investments in suitable protection measures in the most endangered portions of the cable route. Also, a re-routing to a more advantageous area might be considered.
Shield wires or other metallic structures can be considered as protective elements. A beneficial effect could be demonstrated with FEM calculations.
The models used in this paper (hemispherical model, FEM) represent a first approach. Lightning bolts may travel in the soil unpredictably and may endanger the cable system from a larger distance than calculated here. Future research is encouraged to investigate the phenomena further.

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