Electrical stress on the outer insulation of buried cables due to a nearby lightning strike to ground

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Abstract—Field experience indicates that cables buried in soil either directly or in a non-metallic pipe can be at risk due to nearby lightning strike to ground. The triggered lightning experiments provided valuable quantitative information on the subject. There are many questions posed by these observations which motivated a detailed analysis of the electric stress on the cable jacket/sheath, the outer water impervious insulation layer. After identifying the prevailing stress, this work evaluates the dependency of the stress on the associated parameters for the cases of strike to ground and strike to a counterpoise. Possible role of soil ionization is discussed. The role of counterpoise and its protective action are analyzed.

Keywords—Lightning strike, Buried cables, Counterpoise, Electrical stress, Current dissipation, Soil breakdown, Cable sheath, Soil conductivity, Floating potential, Insulation

I. INTRODUCTION

Cables buried in soil either directly or in an insulating pipe are not immune to lightning induced disturbances and damages. As early as 1945, Sunde [1] reports fusing of cable pairs, holes in the sheath, and furrows longer than 100 feet due to lightning stroke arcing directly to the buried cable. By assuming that the outer jacket will eventually be in direct contact with the soil, a frequency domain analysis using wave theory for transmission line was presented. Voltage between the sheath and the cable conductors was extensively analyzed for different scenarios which included direct arcing to the cable, strokes to ground not arcing to the cable, two-layer soil model, cables with insulated sheaths, soil ionization and remedial measures are also discussed.

Most of the following works on lightning stroke arcing to the cable sheath adopted the Sunde’s work. For example, it was extended to include insulating jacket with small specified number of punctures [2]. Combining the previous works on development of breakdown channels in 2D geometry, non-linear circuit model for switching the breakdown channel to the cable, and the transmission line model for wave response is employed in [3] for the overvoltage prediction.

A more dangerous situation for the buried telecommunication cables is considered in [4]. An arcing to the buried cable can occur during a strike to the overhead lines. If the strike results in power follow current, the arcing to the cable will continue resulting in much more damage than that caused by the lightning itself. This aspect was studied in [4] and safe distance criteria for avoiding lightning caused power frequency arcs have been presented.

For the protection of buried cables against direct strikes, the protection zone of buried shield wires is defined in [5]. The sparkover between the buried shield wire and the cable is also considered.

Damages to the buried power cables are observed when nearby object is struck [6]. This was investigated in detail in the triggered lightning experiments at International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida [6] – [8]. The damages observed in these experiments range from a minor puncture of the cable jacket and melted neutral wires, to extensive puncturing of the jacket and the melting of nearly all of the neutral wires [7, 8]. For the cable housed in PVC conduit, after making a hole in the conduit and melting the insulating jacket, the stroke terminated on the concentric neutral wires. The water leak through the punctured jacket results in corrosion of the neutral leading to a delayed failure.

Similarly, damage to the runway lighting system is possible. Triggered lightning experiment was conducted on a test runway lighting system at the ICLRT [7], [9]. Resulting currents in the counterpoise, single core lighting cable and driven rods were measured along with the voltage difference between the counterpoise and cable. In the above two experimental studies, the damages to the terminal equipment are also investigated.

There are few works on induced currents in the buried cable due to a strike to ground. For example, the induced currents in the buried cable were studied both theoretically and experimentally at the ICLRT [7, 10]. These are not of much interest to the present work, which is dealing with stress on the outer insulation.

In most of the earlier theoretical works, if not all, on direct arcing to the cable due to a strike to ground in the close vicinity, the following assumptions are either implicitly or
explicitly made. Firstly, the sheath of the cable is at ‘earth potential’ and hence (i) it disturbs the current distribution in the soil and/or (ii) spark channels inside the soil seek the cable. While the literature on direct arcing to the cables during a strike to ground is complete in their own perspective, these issues require a further scrutiny. Considering this, the present work was taken up and it aims to basically identify the actual stress (electric field) on the cable jacket (outlet insulating sheath). The basic issues that will be investigated are: (i) what would be the genesis of the electrical stress on the jacket due to lightning current in the soil, (ii) what is the role of operating/induced voltage, (iii) what are the parameters that govern this stress, (iv) what could be the role of counterpoise and (v) why is the buried cable without any counterpoise being sought by a strike in the close proximity. In order to focus on the basic problem, the contribution due to induction to the cable/counterpoise and that due to wave nature of their response are ignored. It has been shown in the literature that for close regions spanning a few tens of meters, the quasi-static approach is quite accurate [11]. Incidentally, the electric field outside the cable due to a nearby strike to ground has been evaluated under further simplified assumption in [12], which does not provide answers to all of the questions listed above.

II. STRESS ON THE SHEATH

The electrical conductivity of the soil is known to vary with depth and season. The moisture content affects both the conductivity and the permittivity. However, these changes do not alter the analysis and its results to follow.

As the main focus of this work is on the electrical stress on the outer jacket (outer protective insulating cover), the term conductor here is employed to represent either the central conductor for cables without shield/braid/neutral or the neutral/metallized braid for shielded cables. Also, even though the analysis is carried out for a direct strike to ground, most if not all, observations can be extended to the case of strike to isolated grounded object.

A. Stress due to operating voltage

The voltage on the core for cables without outer metallic braid and any accidental voltage on the outer metallic braid of shielded cables, results in electric field distribution in the surrounding media. This holds true whether or not the cable or the system to which it is connected is grounded or not. Owing to soils very small relaxation (ρ ε) time constant, which is less than some microseconds even for soil with resistivity of $10^4 \Omega\cdot m$, electric field in it will vanish quickly. This is realized by an accumulation of charges on the outer surface of the cable jacket. As a result, all the voltage and hence the electric stress will appear across the outer insulating layer. The above component of the electric stress will be independent of any current in the soil and will not change with the soil ionization due to any external sources.

B. Structure of the electric field in soil

The flow of current in the soil is associated with both conduction current density and the electric flux density, $J = \sigma E$ and $D = \varepsilon E$, respectively, where $E$ is the intensity of electric field, $\sigma$ is the electrical conductivity and $\varepsilon$ is the permittivity. The conduction current will be diverted by the outer insulating surface of the cable, which is necessarily associated with accumulated surface charges (in a time period dictated by the relaxation time constant of the soil). As a result, the normal component of the electric field vanishes at the outer surface of the cable leaving only the tangential component. It may be noted here that this accumulation of surface charges on the outer surface of the cable is independent of the charge what has been accumulated due to the voltage on the conductor (discussed before).

For the purpose of illustration, the situation under quasi-static regime can be crudely represented in terms of distributed circuit shown in figure 1. Here the capacitors are employed to approximately represent the charged outer surface of the insulating sheath and the charges formed on the conductor inside. The resistive elements represent the conduction in soil, and due to the high dominance of the conduction current, capacitors across these resistors, which would represent the displacement current in soil, are neglected. For all practical scenarios, the current drawn by the capacitors representing the cable sheath would be a negligible fraction of the current through the resistive branches. The voltage across any of the capacitors is then solely governed by the resistive network and it would be a small fraction of the voltage at the current injection point.

![Fig. 1. Distributed circuit model for illustration](image)

For the initial time period, the conductor/metallized braid inside acts as a floating conductor, during which a dipolar charge distribution anti-aligned to the direction of external current flow occurs. In any case, to render the conductor cross section to be a zero field region conversion of the ambient tangential electric field on the outer surface into a normal field on the surface of the conductor inside occurs. The charge on the outer surface of the cable will also be influenced by the internal dipolar charge separation.

Depending on the length of the cable and the grounding point, if any, the following phenomena subsequently occur. Firstly, the transients within the conductor inside damp down taking the whole length of the cable to a single potential, which enhances the maximum stress on the outer insulation occurring in the region close to the current injection point to the soil. Secondly, if the cable is connected to a grounded system, the
electric field produced in the soil by the current flow tends to bring in the remote potential, which could prove to be detrimental.

Therefore, the magnitude of the resulting stress would be dependent on the type of the current source (point or line), distance to the source, dimensions of the cable, and the thickness of outer insulating layer. At higher frequencies (> 1 MHz) due to the existence of displacement current, a small normal component of the electric field may exist on the outer surface of the cable sheath, which for all practical purposes has negligible effect.

In any case, it may be noted here that the current flow in the soil is not affected (except for a very short time duration governed by the soil relaxation time constant, which is required for the surface charges to readjust to the modified scenario) by the changes in the voltage of the conductor inside. The electric field lines, which for all practical cases in the soil are identical to the current flow lines, are diverted away from the cable.

The other important inference that can be drawn from the above discussion is that the stress on the outer insulation of cable due to lightning current in the soil is governed by the relative potential and its gradient in the surrounding soil. Therefore, unlike the situation with the field occurring in insulation (air/liquid/solid), stress cannot be evaluated as the voltage between the source (injection) point and the conductor inside; rather it is to be evaluated by the difference between local voltage distribution across the outer insulation of the cable and the (resulting floating/acquired) voltage of the conductor inside.

In order to provide a more illustrative description of the prevailing fields for both initial and later time periods, specific situations are suitably modeled with permissible simplifications. The goal here would be to deduce a clear picture of the salient features of the problem rather than providing quantitative data. Note that, due to the low values of the product $\mu_0\sigma$ for soil, the eddy current effects are generally neglected in the grounding problems.

In the following, the numerical field computation methodology employed will be described along with details of underlying assumption. Subsequently, it will be employed to evaluate the stress and its dependency on various parameters.

C. Field computation methodology

For a quantitative analysis, the required field computation is taken up with the extension of charge simulation method [13] for current distribution around the cable, as well as the electric field inside the sheath. As mentioned before, for this basic study, soil is treated as a homogenous medium. The presence of air above is handled through the method of images. The outline of the procedure involved is as follows.

In order to handle the conduction current and the electric flux (displacement current for higher frequencies) simultaneously, the material properties are taken as complex with real part being formed by conductivity and the imaginary part by the product of angular frequency and the electric permittivity. Two conditions, the continuity of generalized current density on the outer surface of the cable and vanishing field on the conductor/braid inside, are simultaneously imposed.

The discretisation by the charge simulation method involves simulation sources to be kept outside the computational domain [13]. Accordingly, the discrete simulation sources are kept inside the conductors with contour and check points being on the conductor surface. While for the material interface, a pair of sources on either side is placed with a condition that for any evaluation in the given medium, sources within that medium are to be excluded. As mentioned earlier, to model the air-soil interface, images of these simulation sources are considered. For modeling of the vanishing field on the conductor, the unknown (relative) potentials at all its contour (sample) points are forced to be the same along with the constraint that total charge is zero. The same methodology applies to every floating conductor.

In order to deduce the clear description of the field, the following specific cases are considered: (i) a counterpoise over a cable dissipating current uniformly over its length, (ii) a strike to ground near a cable without counterpoise, (iii) strike to ground near a counterpoise, (iv) strike to ground near a counterpoise and cable pair. The first case is for illustrating the circumferential stress distribution over the cable along with its dependency on various parameters. The second case depicts a practical scenario and it is intended for differentiating the situation at initial and later time periods. The third case is to bring clarity on non-existence of zero potential. The fourth is for the counterpoise and cable pair to check the possible reduction in the stress due to the presence of counterpoise.

Further, as discussed before, due to the dominance of conduction current in the soil, the electric field in the soil is directly dependent on the instantaneous current. In view of this, all the analysis is carried out for current normalized to unity.

D. Cable with counterpoise

For a first level of analysis, a simplified model involving a counterpoise dissipating current uniformly over its length at a rate of 1 A/m is considered. The counterpoise is placed directly above the cable with both of them being parallel to the air-soil interface. This 2D model is not that realistic; however, it does serve well for some basic analysis. The conductor (outer braid or conductor for cables without braid) of the cable is either held floating or connected to the ground at specified depth. For augmenting the stress, the connection depth is taken as 2 m. The corresponding grounding resistance is not much of importance in the case considered, wherein the outer insulating jacket is intact. The numerical error in the simulated (relative) potentials using the charge simulation method was kept well below 0.001%.

The default values of the parameters considered are: depth of the counterpoise = 0.3 m, depth of the cable = 0.6 m, outer radius of the cable = 1 cm, thickness of the insulation = 2.5 mm, conductivity of the soil = 0.01 S/m and its relative permittivity set to 3. For the outer sheath of the cable, conductivity (not really important) is set to 10-12 S/m and the permittivity is set to 4. The various dimensions are taken here
only as an example and the inference to be drawn will not be limited to these particular dimensions.

It is verified that the permittivity of the soil, even when set to 81, has some noticeable influence only at frequencies closer to 1 MHz, where the electrical stress in the cable sheath reduces by 9% and possesses an appreciable imaginary component. Therefore, the analysis can be extended to almost entire current duration.

In order to quantify the dependency of the electric stress in the outer sheath of the cable, a parametric analysis was carried out with ground conductivity, outer radius of the cable, thickness of the (outer) insulation layer, and relative distance between the counterpoise and the cable as the variables.

With regard to the potential of the braid/conductor, two distinct cases have been considered. In order to model unearthed system, conductor is held floating, and, as a demonstration example for earthed system, conductor is considered to be in contact with soil at an arbitrary depth of 2 m. Sample simulation results obtained are presented in figure 3, all of which assuming that no soil ionization has occurred.

Figure 2 presents the equipotentials inside and around the cable. Here, only the relative potential with respect to an arbitrary far away reference point will be evaluated for two reasons. Firstly, as the geometry considered is of infinite length and that the total current injected is not zero, absolute potential cannot be defined. Secondly, for the stress on insulated cable only the value of the tangential field along its surface assumes prominence. Even when the cable is grounded, the ground point will be at some relative potential with respect to the same reference point. The figure 2(a) depicts the field distribution outside the cable, while figure 2(b) presents it for the jacket (outer insulation layer). Due to the small range of potential in the insulation the two plots could not be combined. These plots clearly indicate the conversion of external tangential stress to a normal stress inside the sheath.

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Simulation results indicate that with increase in separation distance reduces the relative potential and its gradient in soil, which in turn leads to reduction in the stress on the outer
sheath. On the other hand, for the same reason that the relative potential and its gradient increase with the soil resistivity, stress on the outer sheath is found to increase with the soil resistivity as well.

Similarly, simulations were carried out to examine the influence of the thickness of the outer insulating sheath (jacket) on the resulting stress. Keeping the outer radius the same, the thickness of the insulation and hence radius of the inner conductor/braid was varied. As the electric field outside is not altered, the relative potential outside remained the same. As a consequence, the stress across the outer sheath varied inversely with its thickness.

Even though the situation considered above is hypothetical, it has provided the required basic insight. Other cases, which are more realistic, will be considered next.

**E. Strike to ground near a buried cable**

We now consider the case of a lightning strike to ground above the buried cable with no counterpoise. As before, two distinct cases will be considered namely, braid/conductor is floating and it is in contact with the soil at one end. The computational time depends on the thickness of the jacket, radius and length of the cable. In order to accommodate some reasonable cable lengths, the outer radius of the cable and the thickness of the jacket are chosen to be large. Simulations were carried out for a 96 m long cable of 8 cm radius with 4 cm thick jacket buried at 1.9 m depth. The stroke current was injected into the soil at different locations and no soil ionization was considered. For brevity, only the results for stroke current injected above the midpoint of the cable are presented in figure 4.

In the presence of nearby lightning strike, cable will experience induced fields produced by lightning channel and by current in the soil. Due to the initial wave response demanded by the finite velocity of propagation of the current in the conductor, every piece of the conductor can possess independent dipolar charge separation. The resulting stress across the thickness of the sheath is approximately evaluated and is presented in figure 4(a). The stresses at equal increments of 0.45 m along the length of the cable measured from the midpoint (above which the current injection occurred) are plotted in figure 4. Since the role of conductor is not completely set in, the stress for the above case will be the lowest.

The final stress evaluated for the case of ungrounded cable is presented in figure 4(b). As the whole length of the conductor is at the same floating potential, stress on the sheath gets enhanced. For the same reason, the stress will reverse its sign as one moves towards the end, wherein the floating potential of the conductor would be higher than the local relative potential in the surrounding soil. Corresponding analysis with a counterpoise running above the cable and dissipating current at a rate of 1 A/m indicated a stress which is lower by a factor 3.

Results for the case in which the cable conductor/braid is connected to the soil at one of its ends are presented in figure 4(c). As at later time periods, the remote potential is assigned to the conductor leading to a higher stress across the sheath. For practical lengths of cables, the difference between the stresses for the floating conductor and the grounded conductor cases diminishes.

![Image](image-url)  
**Fig. 4.** Stress on the sheath for different conditions (going from top to bottom would correspond to moving from midpoint to the end of the cable with an increment of 45 cm)

As before, the magnitude of the maximum stress, amongst other parameters, is dependent on the distance to the source and soil resistivity. Whether the conductor is floating or connected...
to the ground at the remote end, the stress on the sheath is quite high. Except for the single core cable without any sheath, the impulse breakdown strength specified for the cable is not indicative of the strength of the jacket rather it is indicative of the strength of the insulation between the core and the metallic sheath. For normal signal and distribution class power cables, the sparkover strength of the jacket is lower than a few to a few tens of kV.

If the soil ionisation is symmetrical, no modification to the above deduction is necessary, unless the intervening cable seriously disturbs the current distribution pattern. The analysis carried out in the previous sections applies quite well in that case. A problematic case, however, can arise when the cable is close to these filamentary spark channels (discharges). These channels possess localized high current densities on their circumference. The resulting tangential gradient across the outer surface of the cable would be high, which enhances the stress on the cables sheath.

Fig. 5. Current shared by the counterpoise (left y-axis) and maximum field on its surface (right y-axis) for a counterpoise with 2 cm radius and 1 m burial depth.

F. Strike to ground near a counterpoise

A buried counterpoise appears to be an ideal example for a “grounded” conductor or for the conductor at “ground” potential. It is obvious that when the current flows in the soil, there exists a potential gradient in the soil defying the concept of an ideal ground. Also, the behavior of the counterpoise at different times can be quite different. Firstly, it would go through a wave response spanning a couple of travel times measured along its length. The impedance offered would be much higher than its power frequency earth termination resistance. Subsequent times are dominated by its distributed inductance, which can offer large impedance even for the initial portion of the tail of the current. Only at later time periods, governed by the length of the counterpoise and decaying rate of change of stroke current, counterpoise will be at its full action. Even under this regime, the total current shared by the counterpoise, when it is away from the soil ionization zone, will be a function of its length, soil conductivity, and distance to the source. For the purpose of illustration, a numerical simulation for a single layer soil model has been performed and the results are presented in figure 5. A 2 cm radius counterpoise is considered to be buried at a depth of 1 m. The soil ionization is ignored. It is worth noting that even though the overall earth termination resistance of the
counterpoise can be quite low (1.9 Ω in this case), the current needs to flow in the soil to enter it and hence there exists a finite resistance between the strike point and the counterpoise. As a result, the current shared by the counterpoise presented in figure 5 can be seen to be a fraction of the incident stroke current.

In order to check whether the concentration of current flow lines on to the counterpoise can significantly enhance the electric field gradient in the soil, field is also computed and the results are presented in figure 5. Even under the assumption that stroke current does not ionize the soil, field on the counterpoise can be seen to be quite high even when the strike point is 10 m away. For median first stroke currents, the resulting field is sufficient to cause a local breakdown of the soil.

Fig. 6. Stress on the sheath for a cable and counterpoise pair under different conditions (going from top to bottom would correspond to moving from midpoint to the end of the cable with an increment of 45 cm)

G. Strike to ground near a cable with a counterpoise

Next the case of cable protected by a counterpoise running above it is considered. Simulations are carried out for a direct strike to ground in the vicinity of the cable. The details are essentially same as for buried isolated cable case dealt in section II E, except that a 2 cm radius counterpoise is now buried at a depth of 0.5 m. For illustration a strike directly
above the midpoint of the cable is considered. The initial wave and subsequent inductive regimes are not dealt with here. The counterpoise due to its continuous earth connection is expected to settle down faster than the insulated cable. The results which will be presented here correspond to late time periods.

In the absence of soil ionization the stress on the sheath/jacket, presented in figure 6(a), can be seen to be reduced by a noticeable amount compared to the floating cable case (figure 6(b)). However, the reduction is not significant due to the limited current collection ability of the counterpoise. It is observed that the counterpoise collects current over considerable length spanning several meters to tens of meters (depending on the length of the counterpoise and the distance between the counterpoise and the strike point). As a result, the current distribution in the soil around the cable section closest to the strike point is not significantly altered. As compared to the same geometry, but with counterpoise dissipating current at a rate of 1 A/m, the stresses are higher by a factor slightly above 2.

On the other hand, if arcing occurs to the counterpoise, then it will tend to distribute the current over longer lengths, at least after the initial transient period. The corresponding stress presented in figure 6(b) can be seen to be significantly lower than in the case presented in figure 6(a). Therefore, it is inferred that the presence of counterpoise by itself does not reduce the stress on the jacket/sheath by a large amount, however, arcing to the counterpoise from the strike location can reduce the stress on the jacket significantly.

III. SUMMARY AND CONCLUSIONS

In this work we investigated the stress on the outer jacket of the buried cable due to a strike to ground nearby. A quasi-static modelling approach was employed to investigate the electrical stress appearing on the jacket, the outer water impervious insulation sheath of buried cable. Soil model was simplified by assuming linearity and homogeneity. Both conduction and displacement currents in the soil and insulation were taken into account in the analysis by employing complex material property. The charge simulation method was employed for the numerical field evaluation. The inferences drawn from the work, not necessarily limited to the geometry considered, are as follows:

(i) The voltage on the core (for cables without sheath) and any accidental voltage on the outer metallic braid (for cables with sheath), will act independently on the sheath, irrespective of any current in the soil.

(ii) Any current in the soil is diverted away from the outer jacket.

(iii) For the case of stroke current entering through a counterpoise running above the cable, the stress on the sheath is basically dependent on the soil resistivity, radius of the cable, thickness of the sheath, and distance between the cable and counterpoise.

(iv) For the case of cable without counterpoise, the length of the cable also plays some role. For the later time periods, the remote connection to the cable becomes important in determining the stress as it would bring the remote earth potential. In any case, depending on various parameters, the stress on the jacket can be higher than the impulse breakdown strength of the insulating jacket.

(v) Soil ionization, due to its filamentary nature can enhance the stress if it occurs close to the cable.

(vii) The counterpoise needs to get through initially wave and later inductive regimes to attain the state of an effective buried conductor. The surface field for median currents is quite substantial even at a radial distance of 10 m, which can lead to a breakdown.

(viii) For the case of floating cable, the presence of counterpoise above slightly reduces the maximum stress on the jacket. However, arcing from the strike point to the counterpoise can reduce the stress on the jacket significantly.

In summary, this work has clarified some of the basic issues pertaining to the stress on the cable jacket, as well as, the role of counterpoise during a nearby strike to ground or grounded object.

REFERENCES