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Effect of lightning mast placement on underground power cable jacket stress within high voltage substations

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Abstract

This study aims to investigate the impact of lightning masts placement on underground cables within high voltage substations. While the subject of lightning discharges near to underground cables has been covered with open cable runs and wind farms in many papers, this study focuses on lightning events within high voltage substations considering the associated effective zones, which were not covered in the available literature. Substations built within areas prone to high lightning activity experience frequent discharges that cause the potential rise of the earthing system into hundreds of kilovolts. The potentials propagating within the soil and the earthing grid affect underground cables jackets terminated within the substation. The numerical analysis of the problem is carried out using Current Distribution, Electromagnetic fields, Grounding and Soil structure analysis (CDEGS) software engine for different configurations of lightning mast placements with varied separation, electrode placement and length, soil resistivity, and lightning current. Study findings indicate that provision of lightning masts/down conductors as far as possible or at least twice the effective zone radius from cable termination/route electrodes ensures relatively lower stress voltages. Electrodes with effective zone radius length placed as close as possible to lightning masts further reduce the attainable jacket stress voltages.

Keywords: substation earthing; lightning mast placement; high voltage; underground cable; effective zone radius.

I. Introduction

Lightning protection air terminations represent a vital part of high voltage substation switchyards [1]. Many models are available to design the lightning protection systems based on various formulae for lightning stroke current and associated rolling sphere radius [2]. During a lightning stroke discharged into the substation earthing system, the soil will have a transient potential gradient within the substation and nearby [1]. The gradient causes underground cable jacket stress that can exceed its insulation strength and cause a breakdown of the jacket compromising its integrity and the cable lifetime [1].

The lightning protection systems intercepting lightning strokes exceeding the design current help rationalising the surge arrestors selection by diverting stroke currents to the substation earthing system. A traditional sphere radius of 24 m is used, which corresponds to a stroke design current of about 4.2 kA based on the electrogeometric method (EGM) [2]. Some other utilities suggest a sphere radius of 43 m corresponding to 10 kA striking current, which is in line with the rated discharge current of most station type surge arrestors. The rationale behind that is to allow surges less than 10 kA to penetrate the shielding system, given these surges will be neutralised by surge arrestors typically installed near to important equipment within the substation. Surges higher than 10 kA will be intercepted by the lightning protection system and diverted to earth. Typical locations for surge arrestors within high voltage switchyards are line entries, power transformers, and cable sealing ends.

The impact of lightning discharges on underground cables has been studied extensively with respect to testing, open runs, and wind farms. Gomes *et al.* [3] have used ATP modelling to study the lightning discharge impact on cable sections terminated to towers near substations with special

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focus on the frequency dependency of soil and towers earthing systems. It has used a lumped impedance representing the earthing grid instead of detailed modelling for the grid. Narajo-Villamil *et al.* [4] studied lightning induced surges in underground cables with focus on building reinforcements and internal earthing. Arshad *et al.* [5] listed a study on lightning effects on 132 kV underground cables using ATP but without considering substation earthing systems. Cao *et al.* [6] studied the effect of lightning strikes on sheath voltage limiters in open run applications. Tanaka *et al.* [7] document a detailed study on the use of buried shield wires to improve the open run underground cable lightning performance considering the diversion of surges from the cable. Kangro *et al.* [8] detailed different modelling approaches on cable sheath representation and the effect of lightning high frequency components on results. Wu *et al.* [9] presented a typical study on open run underground cable metallic sheath induced voltages due to lightning discharges with focus on soil stratification effects. Aniserowicz *et al.* [10] documented a comparative study between CDEGS modelling and semi-analytical approaches regarding lightning voltage and current distributions within an underground cable system. Chen *et al.* [11] demonstrated site measurements of transferred surges through soil with rocket-triggered lightning strikes and associated response of surge arrestors. Jiao *et al.* [12] listed experimental results for coaxial cables lightning response and associated coupling using an impulsive generator setup. Güneri and Alboyaci [13] analysed the accuracy and validity of different modelling techniques for high frequency lightning response with underground cables return impedance. Shehab *et al.* [14] carried out a detailed lightning transient study of power transformers within a thermal power plant where the effects of lightning surges can be detrimental to equipment operation and cause excessive blackouts. Liu *et al.* [15] proposed a new method to estimate the lightning induced voltages on overhead lines and single core underground cables open runs. Sekioka [16] studied wind farm connected substation lightning overvoltage due to underground collector cable sheath propagation of surges impending at wind turbines. Taha *et al.* [17] discussed the performance of a lightning protection system for a 110 kV substation within an urban area using CDEGS software to estimate the touch and step voltages associated with lightning discharges into the substation earthing grid. Sabiha *et al.* [18] studied the overvoltages and supply continuity associated with backflow lightning surges propagating through lightning protection air terminations of photovoltaic installations. Aref and Anaraki [19] studied the propagation of lightning surges through a transition between underground and overhead connections within sub-transmission substations. Alipio *et al.* [20] studied the lightning surge propagation in mixed overhead-cable lines taking soil frequency dependency into consideration. Q. Liu *et al.* [21] investigated the lightning performance of weather stations and its effects on sheathed cables with requirements on separate lightning electrodes. Goertz *et al.* [22] analysed the HVDC cables response to lightning strokes and stress variation along cable length and the impact on insulation coordination with different station earthing resistances. Lennerhag *et al.* [23] developed a statistical method for estimating lightning overvoltages in HVDC cables and lines, considering shielding failure and backflashover scenarios. Eriksson [24] researched the impact of lightning masts placement on low voltage cable insulation within substations without considering the jacket breakdown or the effective zone concept and the effect of other design parameters on attainable stresses.

This paper studies cable jacket insulation impacted by discharges affecting high voltage substation earthing systems, with a focus on lightning mast location and earthing system modifications that were not covered in the available literature. The paper investigates the impact of the placement of lightning masts and down conductors within a substation on terminated underground cable jacket stress, taking into consideration the effect of varied separation, electrode placement and length, soil resistivity, and lightning current.

II. Materials and Methods

A. Lightning discharge and modelling

Lightning stokes show a probabilistic nature with current ranges from a few hundred amperes to about 200 kA [2]. Several probability density functions had been developed to match field measurements from various countries and territories with variable median and exponent values [1][2]. The general form of the density function is given by equation (1):

$$\mathbf{P(I_p)} = \frac{\mathbf{1}}{\mathbf{1+\left(\frac{I_p}{I_{50}}\right)^x}} \tag{1}$$

where, $P(I_p)$ is probability that any peak return-stroke in any given flash will exceed I_p (kA), I_{50} is 50 % probability peak current, x is exponent, I is lightning peak current (kA). For this study, I_{50} is 24 kA and x is 2.6 are selected.

Hence, a typical stroke in any lightning flash is expected to follow the pattern in Figure 1. The median indicates that 50 % of strokes crest current will exceed this value at any time. The typical probability distribution shows that high stroke currents are less probable but not impossible. The probabilistic nature of the lightning phenomenon is captured in this distribution, where strokes can vary along a very wide range of currents at the same location. Around any calculation period, typically a few years, half of the strokes at a certain area will exceed the median value where the other half will be equal to or less than the median value. Standard 1.2/50 μs current impulse is used to perform the studies.

B. High voltage substation lightning protection

Switchyards are typically protected against lightning discharges by air terminations. This can be in the form of shield wires and/or, preferably,

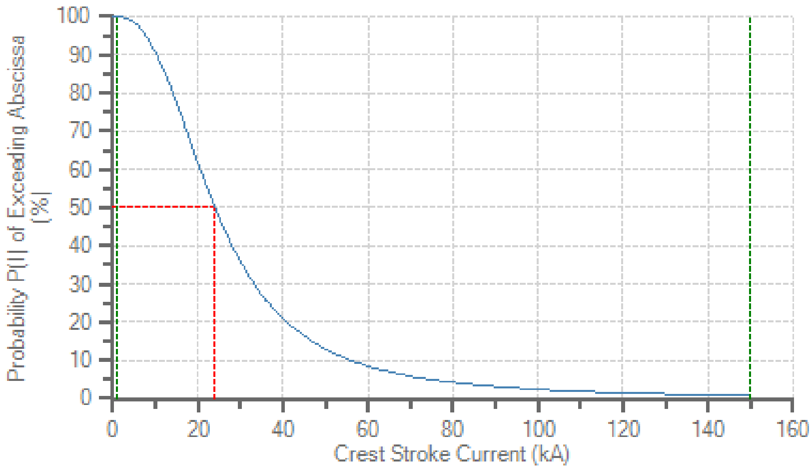

Figure 1. Probability of stroke current exceeding abscissa, 24 kA median value with 50 % exceedance probability is shown

lightning masts (LM), due to the risk associated with shield wires failure onto switchyard live conductors, as reported in [25]. The electrogeometric method (EGM) [2] utilises a rolling sphere with a striking distance as its radius, depending on the striking current. The sphere indicates the areas that a stroke is probable to hit and air terminations are provided to intercept the strokes away from the protected equipment and conductors, as illustrated in Figure 2 [26].

C. Cable jacket insulation

Underground high and medium voltage cables are usually provided with a protective insulating jacket to block moisture and protect the cable from external damage. The jackets made of PVC or HD/LD PE are common. Jackets are not designed to withstand high voltage stresses since the cable metallic sheaths are designed to have a limited potential with respect to soil outside cables [27]. Accordingly, the breakdown of the jacket can cause a puncture pinhole, moisture migration and damage. Lightning damage to cables has been reported in [28].

Typical lightning impulse withstand voltages (BIL) are provided in Table 2 of [27]. Given the cable jacket insulation is non-self-restoring, peak recorded values of non-standard waveforms obtained at the cable jacket shall be compared to jacket BIL [29]. 60 kV is a typical value to consider for jacket withstand voltage for HV cables. Although this value is indicative, higher values may be verified through testing. The jacket BIL is an important factor to avoid breakdown and subsequent moisture damage. Since most HV underground cables are laid directly in the ground due to cost and ampacity requirements, jacket thickness is not perfectly uniform along the cable due to possible abrasion during and after installation. The compromised jacket thickness will result in a lower BIL due to a higher electric field within the jacket. Another detrimental factor that affects the underground cable jacket is the presence of corrosive chemicals in the soil, which must be verified during the installation planning/design stage through soil chemical analysis. The latter is especially true for installations within industrial areas with contaminated soils.

D. Earthning grid performance with lightning discharge

The impact of lightning discharges on substation earthing grids has been studied with several parameters (grid dimensions, conductor spacing, impulse feed point location, soil resistivity and ionization, wave front time and current amplitude) [1]. The critical or effective length concept is introduced to identify the phenomenon of limited lightning impulse propagation due to the dominant inductive effect at very high frequencies associated with lightning discharges. The critical length concept is extended into an effective zone with a radius r_e in metres given by equation (2) [1] for the centre feed point/lightning mast:

$$r_e = 0.34\rho^{0.42}T^{0.32} \quad (2)$$

where ρ is soil resistivity in Ω.m and T is the front time in μs. The effective zone radius indicates the zone of conductors contributing to lightning discharge dissipation. In other words, connected grid

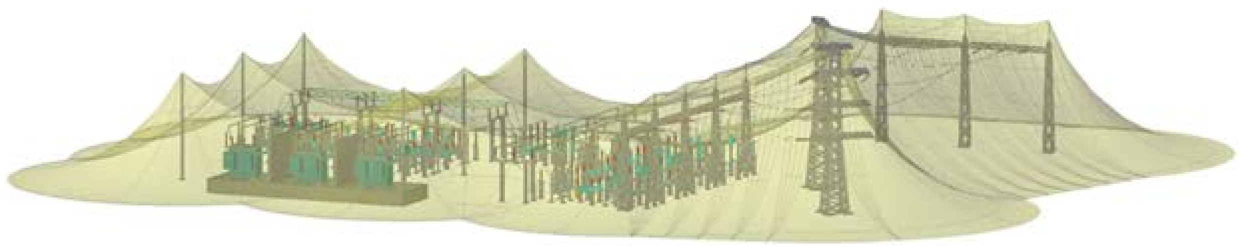

Figure 2. Lightning masts around HV switchyard and rolling sphere concept [26]

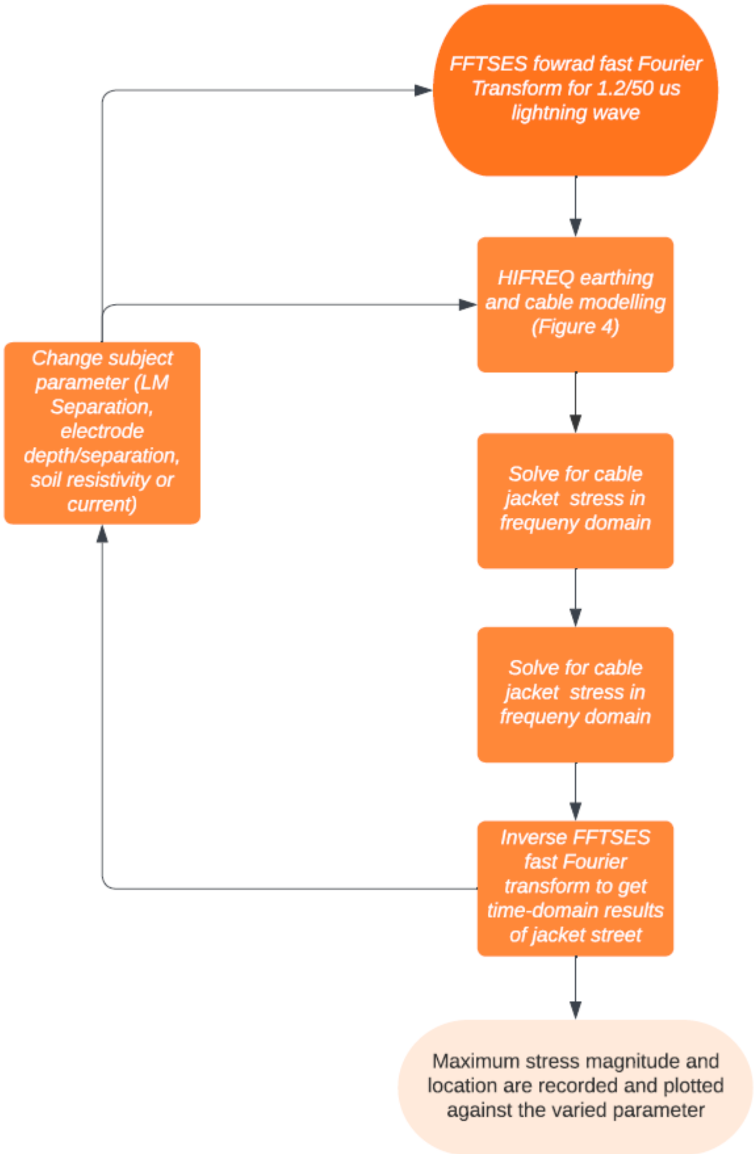

Figure 3. Modelling flowchart

conductors and rods beyond this zone have insignificant effect on grid lightning response, contrary to the power frequency behaviour where additional conductors are typically contributing to reduce the grid resistance and attainable touch, step and transferred voltages.

E. Methodology

The study uses state-of-the-art Current Distribution, Electromagnetic interference, Grounding and Soil structure analysis (CDEGS) software engine. The process is summarised by the flowchart in Figure 3. The process starts with the initial modelling of the earthing grid and cable using CDEGS high frequency analysis module (HIFREQ) software, as shown in Figure 4. The software engine is based on the field theory method and uses the method of moments (MoM) to solve Maxwell's equations in three dimensions. The software does not consider soil ionization [30], a phenomenon encountered with lightning discharges exceeding 100 kA resulting in increases conductive area around affected conductors, especially with concentrated designs. CDEGS fast Fourier transform module (FFTSES) is then used to perform the forward transform of the standard lightning impulse into periodic components with different frequencies, where the software calculates each frequency parameter separately. Inverse Fourier transform is used to recompile the frequency-domain results into time-domain results for attainable jacket stress variation with time. The process is repeated with the varied parameter as indicated in Table 1 for each case and the maximum jacket stress results (magnitude and location along cable) are obtained through the FFTSES and plotted against the variable parameter.

Three main cases are studied in this paper, with parameters tabulated in Table 1. Details of each case are provided below.

1) Case–I.1

The first case under study is for a typical HV substation earthing grid with overall dimensions of 100 x 100 m and 10 m uniform spacing, as shown in Figure 4. The native soil resistivity is 100 Ω.m. One 15 m lightning mast of typical steel construction and a 1.5 m spike above it is considered for impulse feed.

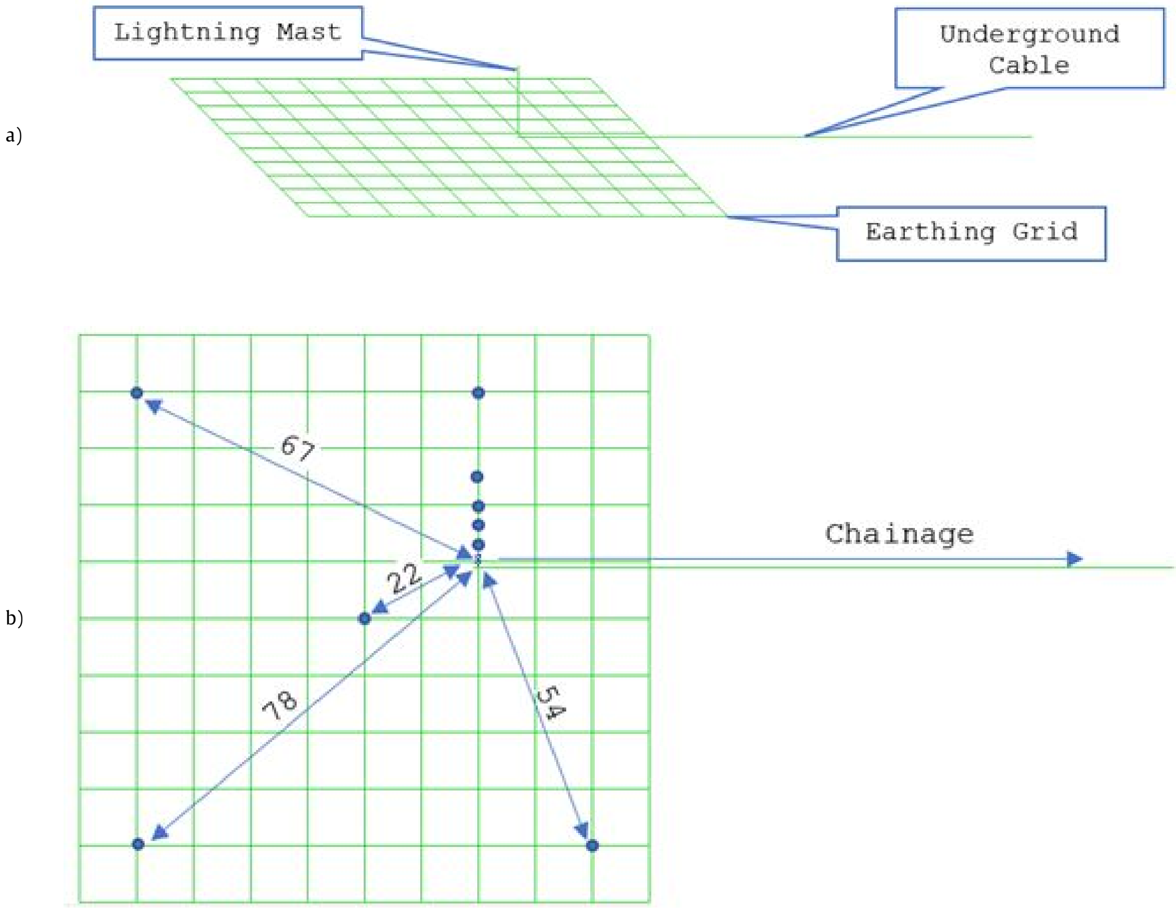

Figure 4. 100 x 100 m, 10 m uniform spacing earthing grid, underground cable, and lightning mast CDEGS HIFREQ model: (a) 3D view; (b) Plan view with LM possible locations shown in blue dots and separation distances in metres as marked. Cable chainage direction shown away from grid

An underground cable terminated at the substation earthing grid and ran outside the substation grid for 1 km. Cable sheath is bonded to the substation earthing grid at the termination point (cable sealing end). Lightning current is set at the median value of 24 kA. The mast location is moved away from the cable/sheath termination point at the earthing grid and maximum jacket stress voltage is obtained accordingly. The earthing grid power frequency resistance is calculated as 0.46 Ω.

2) Case–I.2

The base design is modified with the addition of a vertical rod next to LM. The power frequency earthing resistance is not affected by the addition of a 2.5 m electrode at the lightning mast due to the extended grid area and uniform soil resistivity.

3) Case–I.3

The base design is modified considering a practical spacing in outdoor high voltage substations for the LM and cable sealing end (CSE) ≥ 4 m. The electrode depth is varied to identify the impact on attainable jacket stress. The power frequency earthing resistance is not affected by the increased electrode depth given the extended grid area.

4) Case–I.4

The base design is modified considering a typical 2.5 m deep electrode used to check the effect of moving the electrode away from the LM. The power frequency earthing resistance is not affected by the increased electrode depth given the extended grid area.

Table 1.
Case study parameters

Case	Lightning current (kA)	Soil resistivity (Ω.m)	Mast separation (m)	Electrode depth (m)	Electrode separation (m)	Effective zone radius (m)
I.1	24	100	1:78	0	0	2.5
I.2	24	100	1:78	2.5	0	2.5
I.3	24	100	4	0:30	0	2.5
I.4	24	100	4	2.5	0:15	2.5
II.1	24	500	1:78	0	0	4.9
II.2	24	500	1:78	2.5	0	4.9
III.1	120	100	1:78	0	0	2.5
III.2	120	100	1:78	2.5	0	2.5

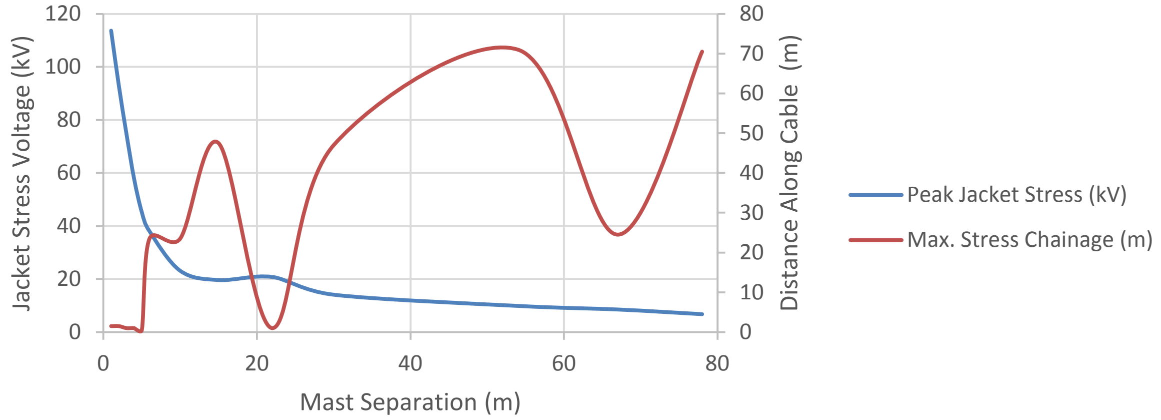

Figure 5. Peak jacket stress voltage and location variation vs. LM separation

5) Case– II.1

The soil resistivity is considered for this case as 500 Ω.m with a similar setup as Case - I. The earthing grid power frequency resistance is calculated as 2.31 Ω. Lightning current is set at the median value of 24 kA.

6) Case– II.2

The design is modified with the addition of a vertical rod next to LM. The power frequency earthing resistance is not affected by the addition of a 2.5 m electrode at the lightning mast due to the extended grid area and uniform soil resistivity

7) Case– III.1

The soil resistivity is considered for this case as 100 Ω.m with similar setup as Case - I but with the injection lightning current of 120 kA peak (5 x 24 kA) representing a value of stroke current with only 1.5 % exceedance probability (i.e., more than 98.5 % of lightning strokes will be less than 120 kA). The earthing grid power frequency resistance remains as 0.46 Ω calculated in Case-I.

8) Case– III.2

The design is modified with the addition of a vertical rod next to LM. The power frequency earthing resistance is not affected by the addition of a 2.5 m electrode at the lightning mast due to the extended grid area and uniform soil resistivity.

III. Results and Discussions

A. Results

1) Case– I.1 results

The attainable jacket stress voltage versus variable separation distance from the lightning mast is shown in Figure 5. The attainable stress voltage typically decreases with distance away from the LM with little or no dependency on placement direction. The location of the maximum stress varies with mast separation and shows a tendency to move outside the substation grid with greater mast separation to the cable termination point. The cable stress voltage suffers a sharp decline beyond 5 m (i.e., twice the calculated effective zone radius). The behaviour follows the concept of effective length that beyond a certain distance along earthing conductor, the potential variation (and hence, resistance) is insignificant regardless of the additional connected conductors.

2) Case– I.2 (modified design – addition of vertical rod next to LM) results

The attainable maximum stress voltage and location is shown in Figure 6. The attainable stress voltage typically decreases with distance away from the LM with little or no dependency on placement direction, similar to Figure 5. Electrode works to dissipate the lightning current at the LM more effectively away from the rest of the earthing grid.

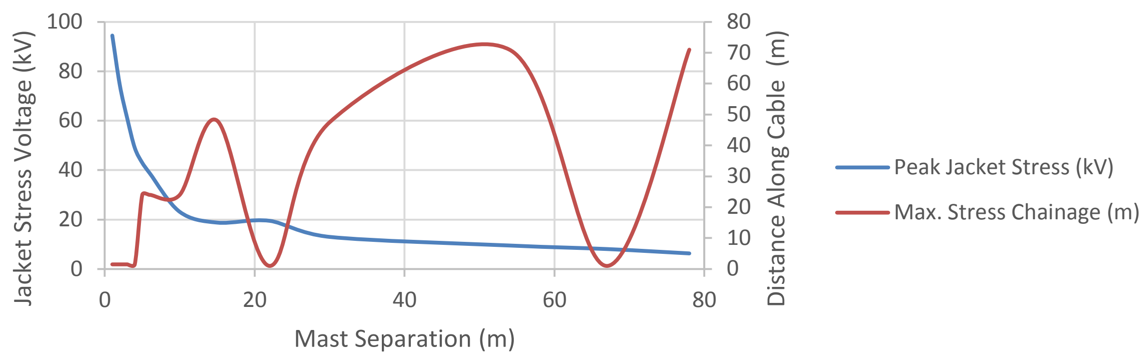

Figure 6. Peak jacket stress voltage and location variation vs. LM separation

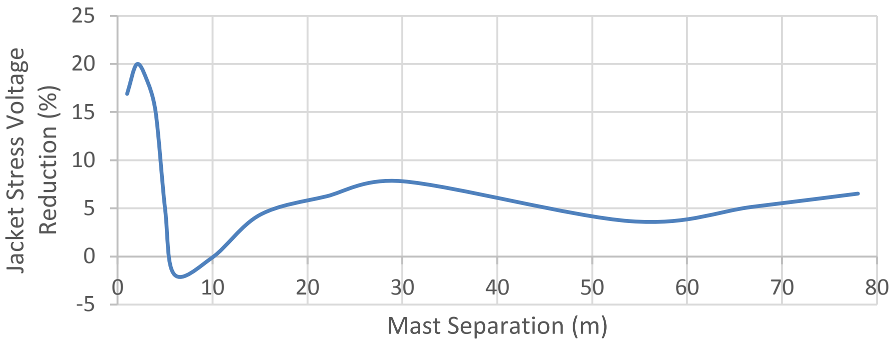

Figure 7. Peak jacket stress voltage reduction with/without electrode vs. LM separation (negative reduction % indicates stress increment with electrode)

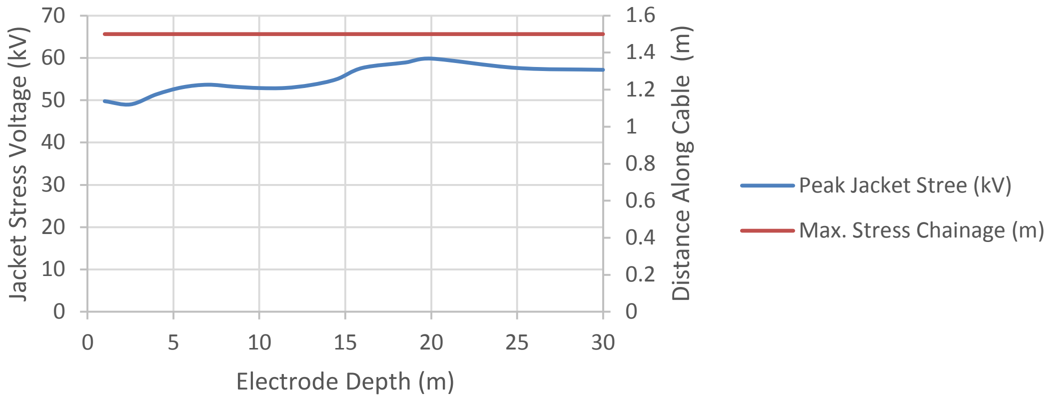

Figure 8. Peak jacket stress voltage and location variation with electrode depth

The effect is paramount with a separation distance of less than 5 m (twice the calculated effective zone radius) with a recorded maximum stress reduction of about 20 % compared to the case with no electrode. Spacings greater than 5 m showed slightly higher stress voltages compared with the no electrode configuration (~2 %) then falls away (>15 m) to about 6 % average reduction. Figure 7 depicts the calculated reduction versus the mast separation.

3) Case– I.3 (modified design – variable electrode depth) results

The results are graphed in Figure 8. The jacket stress increases with electrode depth counterintuitively with more than 20 % rise obtained at increased depth compared with an electrode at a depth equal to the critical length. The behaviour is reversed after reaching a maximum value. No change to the locations of recorded maximum stress is observed. The graph indicates that a shorter electrode is more effective than a deeper one for the same LM separation. While deeper electrodes are more useful in power frequency earthing design, it adds more inductance to the high frequency circuit impeding the lightning discharge.

4) Case– I.4 (modified design – variable electrode location) results

The results are shown in Figure 9. The electrode separation from LM is critical with a sharp increase

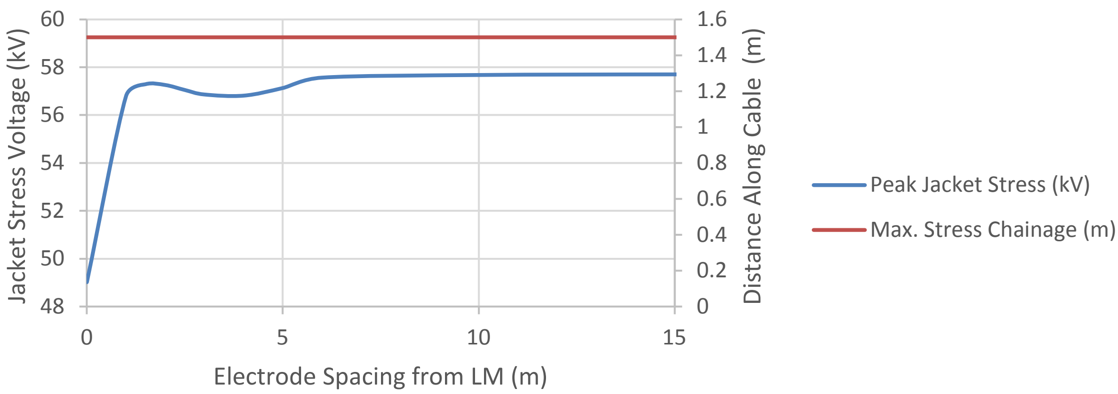

Figure 9. Peak jacket stress voltage and location variation with electrode depth

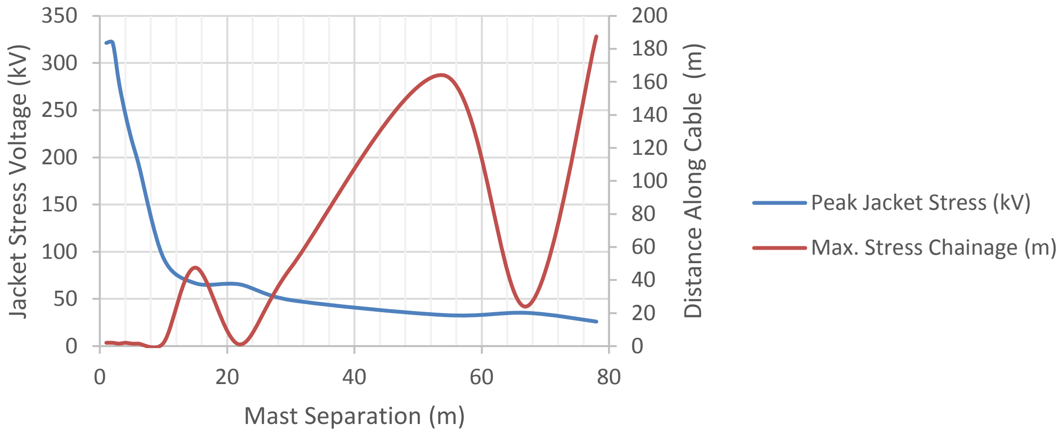

Figure 10. Peak jacket stress voltage and location variation vs. LM separation

in jacket stress voltages (18 %) with ~1 m separation. The jacket stress is almost constant for any electrode separation of more than 1 m. No change to the locations of recorded maximum stress is observed. These results emphasize the importance of a close placement of electrode and LM for mitigating underground jacket stress voltages.

5) Case– II.1 results

The attainable peak jacket stress voltage with variable separation distance from the lightning mast is shown in Figure 10. Like Case – I.1, the location of the maximum stress varies with mast separation and shows a tendency to move outside the substation grid with greater mast separation to the cable termination point. The cable stress voltage suffers a sharp decline beyond 10 m (i.e., twice the calculated effective distance). This indicates that soil resistivity affects the effective distance with a similar pattern compared to the base case. Smoother maximum stress voltage chainage variation is noticed. While the maximum cable stress shows an inverse pattern with the mast separation distance, the chainage of the maximum stress is much affected by the mast location rather than the separation.

6) Case– II.2 (modified design – addition of vertical rod next to LM) results

It is evident that the addition of an electrode reduces the attainable cable jacket stresses, as shown in Figure 11 with a pattern similar to Case-I.2. Smoother maximum stress voltage chainage variation is noticed compared with the 100 Ω.m case. Reduction of the attainable stress voltages nears 25 % at LM separations about the effective zone radius as shown in Figure 12. With the non-linear pattern, the reduction is negligible at about 50 m (~10 times the effective zone radius) with masts far away from the cable sheath earthing point. The reduction again appears with a single peak value approaching 19 % with the mast at the corner location. While most of the hazardous underground cable jacket stresses occur with short mast separations (< twice the effective zone radius), the use of electrodes at lightning masts results in higher reduction at these separations and is effective to control the attainable stresses.

Notwithstanding that the soil resistivity is five times that used in Case-I.1 and I.2 (100 Ω.m) and hence the power frequency resistance, the attainable stress voltages are not elevated by the same ratio, as shown in Figure 13. The voltage rise is less than 500 % and peaks at a separation slightly greater than the effective zone radius. This indicates the non-linear lightning response behaviour of the earthing grid due to the pronounced induction effects of the high frequency component limiting the attainable voltages/stress. The maximum stress is about 82 % of the algebraic proportion, or in other words, a minimum of about 18 % reduction is obtained with

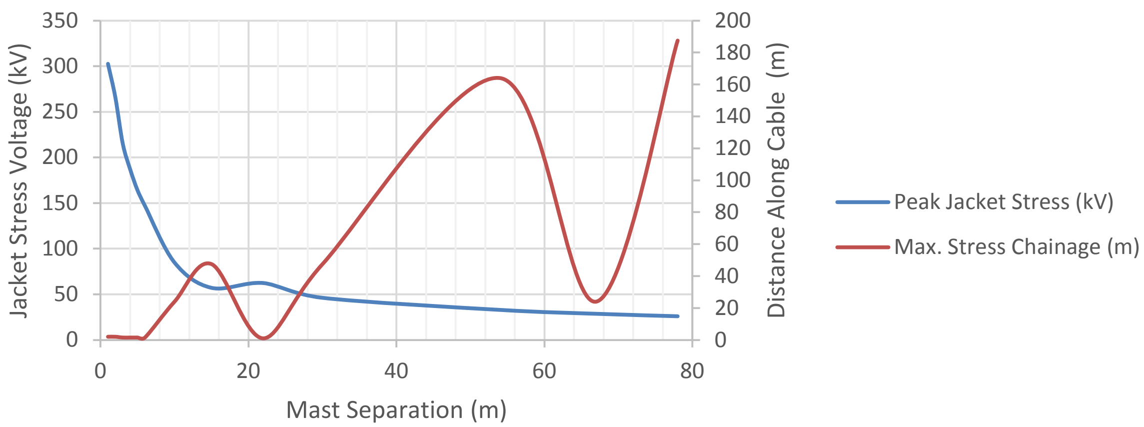

Figure 11. Peak jacket stress voltage and location variation vs. LM separation

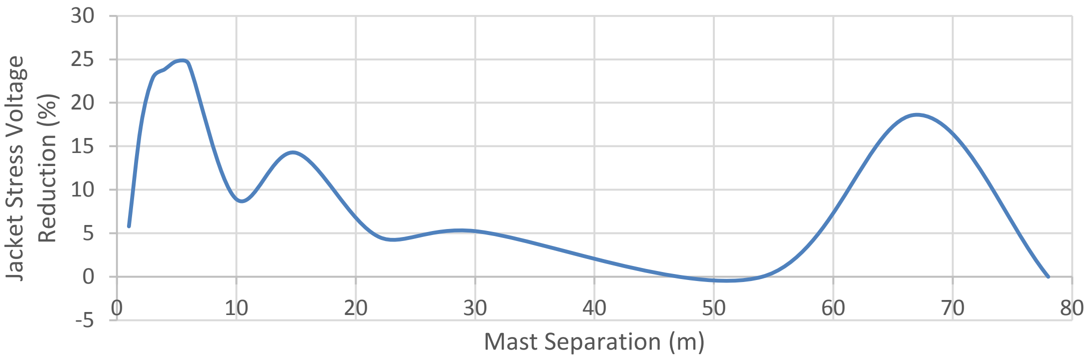

Figure 12. Peak jacket stress voltage reduction with/without electrode vs. LM separation

normalised 500 Ω.m soil. At greater spacings, the reduction is about half of the estimated algebraic proportion value based on normalised soil resistivity. This pattern is also in line with the self-limiting characteristics of lightning surge propagation within earthing grids and the associated reduction in underground cable jacket stress.

7) Case– III.1 results

The attainable jacket stress voltage with variable separation distance from the lightning mast is shown in Figure 14. The majority of steep gradient appears near the LM (~effective zone radius) and the rest of the separations return a very similar value to the 24 kA injection case. The jacket stress "saturates" a few metres away from the injection point regardless of the high stroke current conforming to the effective zone concept due to the dominant inductive component with the high frequency lightning discharge. Similar to Case-I and Case-II, the location of maximum stress varies with mast separation, with a tendency to move outside the substation the greater the mast separation to the cable termination point. The chainage of the maximum stress is much affected by mast location rather than its separation. The self-limiting behaviour is very useful in estimating the cable stress voltage with increased stroke currents where the criticality of mast placement is not affected by the high stroke current compared to separation.

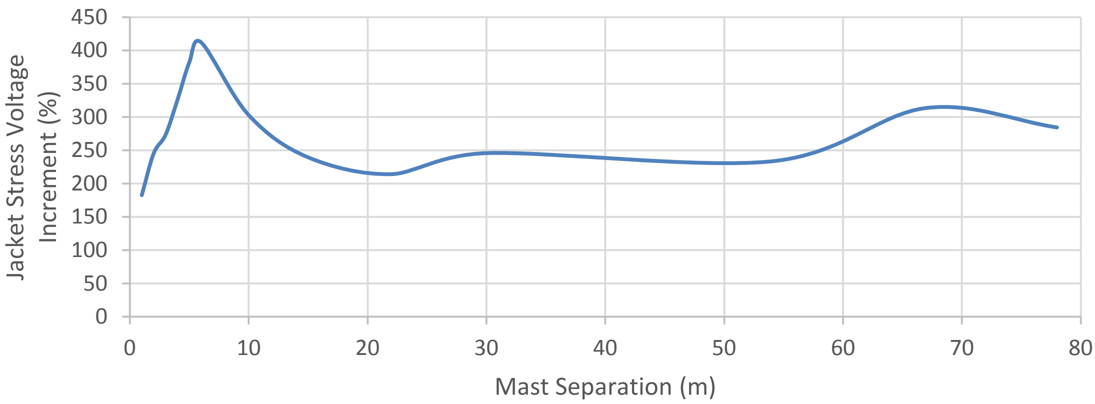

Figure 13. Peak jacket stress voltage increment with 500 Ω.m soil vs. LM separation

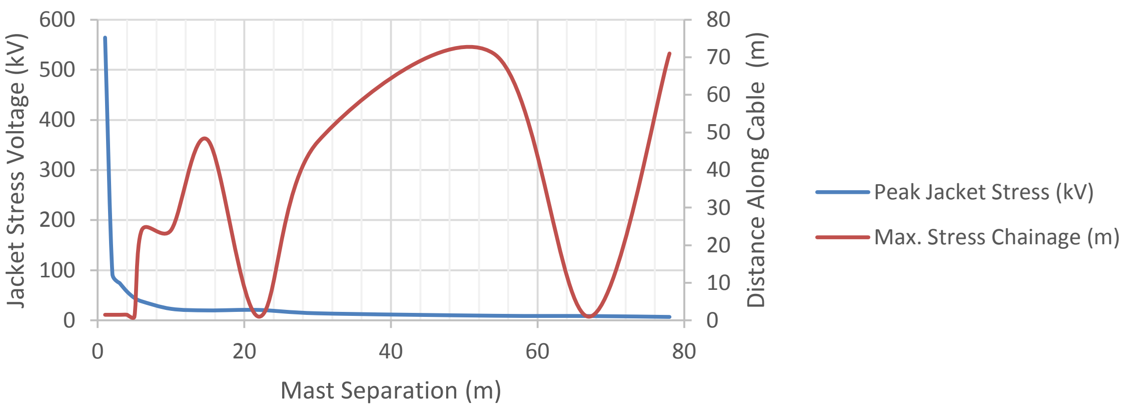

Figure 14. Peak jacket stress voltage and location variation vs. LM separation

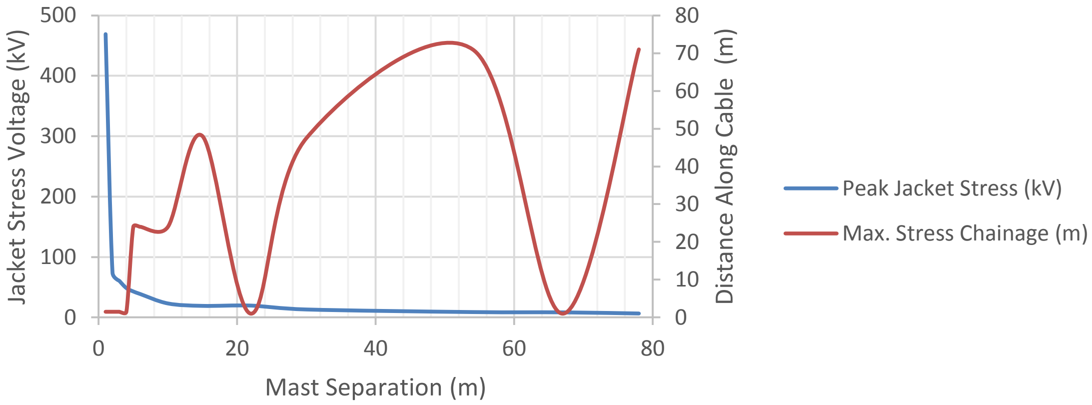

Figure 15. Peak jacket stress voltage and location variation vs. LM separation

8) Case–III.2 (modified design – addition of vertical rod next to LM) results

The addition of a vertical electrode improves the attainable jacket stress pattern similar to the one observed in previous cases, as graphed in Figure 15 and Figure 16. As with other corresponding cases, with most of the hazardous jacket stresses taking place with short mast separations, the use of an electrode at lightning masts is effective in mitigating underground cable jacket stresses at these separations. A steep gradient of jacket stress voltage with mast separation is observed with the self-limiting behaviour contributing to the improved attainable voltages at an underground cable jacket with electrodes installed at LM. No change to the locations of recorded maximum stress is observed with the electrode compared to the case without the electrode in Figure 14. Reduction of the attainable stress voltages near 19 % at LM separations about the effective zone radius, as shown in Figure 16. With the non-linear pattern, the reduction declines sharply at about twice the effective zone radius before dipping briefly and then sustaining a quasi-steady pattern with masts far away from the cable sheath earthing point.

Although the injection is five times the median current (24 kA), the attainable stress voltages are almost identical to Case-I, excluding the placement of LM near the cable termination point (~effective zone radius), as shown in Figure 17. Some locations (20 ~ 60 m separation) provide a reduction of the attainable stress compared with the 24 kA injections. This pattern demonstrates another non-linear earthing grid lightning response behaviour limiting the attainable underground cable jacket voltages/stress. The maximum stress is about 62 % of the algebraic proportion, or in other words, a minimum of about 38 % reduction is obtained with a normalised 120 kA stroke. A 20 % less obtainable jacket stress compared to the 24 kA case is encountered around 1 x effective zone radius before settling at a fractional increase (~10 % and less) at longer spacings.

B. Significant Impact of LM Separation

The lightning response of earthing grids is a complex phenomenon with soil and conductors' interactions [1]. The placement of lightning masts within the substation affects the resultant voltage stresses that appear on underground cables leaving the substation. The provision of electrodes as close as possible to the LM helps reduce the attainable voltage at the cable jacket. The non-linear behaviour of potential distributions with lightning discharge current is evident with reduced jacket stress despite higher injection currents. This is ascribed to the significant inductive effect with high frequency components of lightning discharge and the associated effective length phenomenon.

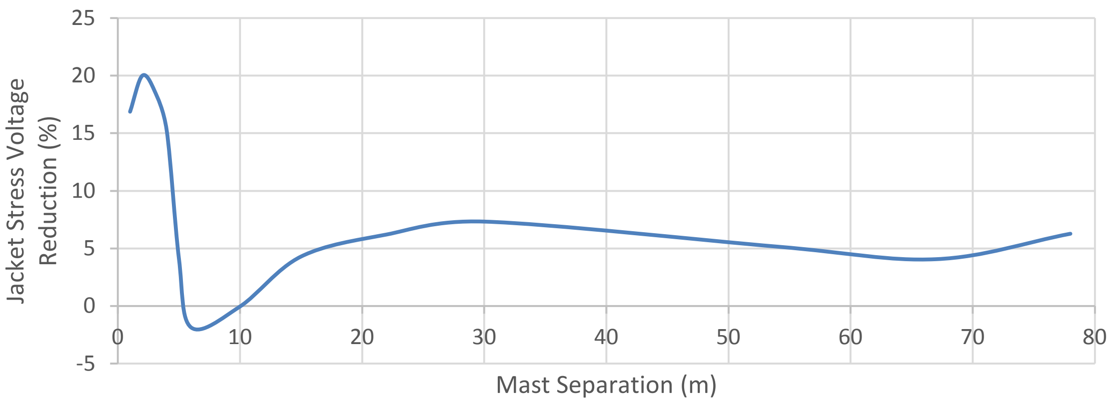

Figure 16. Peak jacket stress voltage reduction with/without electrode vs. LM separation

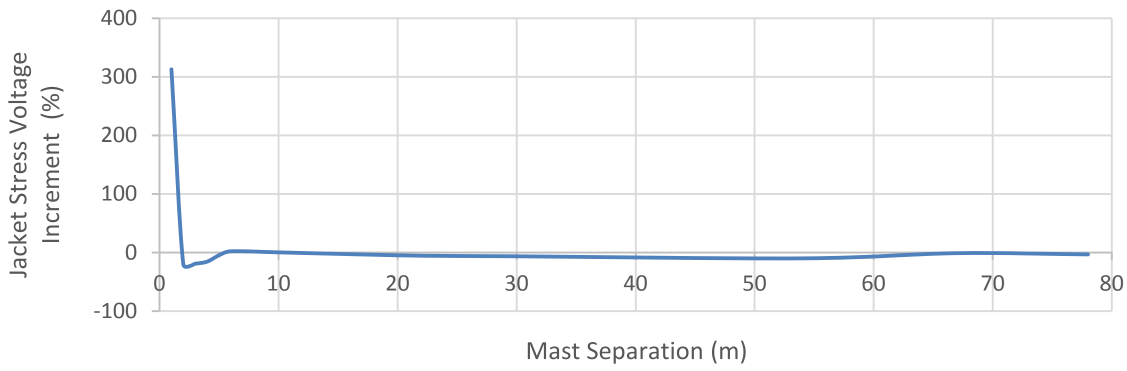

Figure 17. Peak jacket stress voltage Increment with 120/24 kA vs. LM separation (negative increment % indicates stress reduction with 120 kA lightning)

Since the effective length is much shorter than the installed earthing grid, soil resistivity is the single most important parameter in determining the lightning response of earthing grid. Along with separation distance, the severity of the jacket stress on underground cables terminated at the grid can be estimated.

Cable jacket stresses exceeding the respective BIL are likely to take place with almost 50 % of strokes intercepted by LMs exceeding the median lightning current distribution. The most critical zone is the cable termination near the sealing end, where a lightning mast placement is discouraged near a cable termination. The study finding suggests twice the effective zone radius as a buffer separation.

The provision of non-metallic ducts/conduits made of PVC/HDPE strengthens the jacket insulation. For underground power cable routing within substations, especially in the vicinity of LMs, it should be considered as a good design practice by typically adding about 60 kV or more to jacket dielectric strength depending on conduit construction and wall thickness. The study did not consider soil ionization; however, it is not expected to largely impact the results as the conductor diameter has a minimal effect on potential distributions.

IV. Conclusion

The introduction of lightning masts/air terminations within substation earthing grids works as a current injection point. The location of the masts affects the resultant underground cable jacket stress voltages with considerable impact taking place when the cable sheath (or route) is terminated near the lightning mast. The jacket stress is affected by soil resistivity and mast separation. The greater the separation of the lightning masts to the cable termination point or cable route, the lower the jacket stress voltages. Where this is unfeasible, the study finding suggests twice the effective zone radius should be used as a buffer separation between the LM and cable (route/termination). The provision of relatively short (~effective zone radius) electrodes as close as possible to the LM effectively helps reduce the attainable stress voltages. Non-metallic ducts/conduits strengthen the jacket insulation (typically adding 60 kV or more to jacket dielectric strength) and should be considered as a good practice for underground cables within substations, especially in the vicinity of LMs.

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Declarations

Author contribution

M. Nazih is the main contributor of this paper. Author read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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