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Lightning strike to ground – a case study about observed cable damages, risk estimation and protection method

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SUMMARY

In this contribution a case study about the damages to cable sheath is presented which are suspected to be caused by the lightning strikes to the ground in proximity of the cable route. The sheath damages were found on two parallel HVDC underground cable systems where each of them is nearly 200 km long. The damages were found at 10 locations along the cable route after approximately 7,5 years. Damages were not severe enough to immediately damage the cable main insulation system, however these allowed for water intrusion under the sheath. Observations at the locations also revealed a few lightning damaged trees in the proximity of the cable systems. Based on the nature of the damages it was decided to investigate the case for the risk of sheath damages caused by lightning strike to the ground. The lightning statistics were obtained from the national meteorological and hydrological institute. Based on this data the historical lightning strike frequency could be calculated for the cable corridor during the selected time period. Using the lightning statistics the probabilities for exceeding certain lightning current magnitudes were calculated. FEM modelling was used to evaluate the effect of the lightning current magnitude, distance to the cables and ground resistivity on the critical E-field in the cable sheath. Combining all the above it was possible to estimate the expected frequency of the sheath damages caused by the lightning strikes. The calculations agreed well with the observed damage frequency which resulted in expressed MTBF of 0,5-1 years. A protection method using buried shield wires introduced parallel to the power cables was investigated. With increasing complexity of the arrangement, the MTBF could be sequentially improved. The most complex configurations resulted in MTBF of ca 10-20 years, however even simpler configurations can provide adequate protection.

KEYWORDS

Power cables, lightning strike, sheath damage, risk estimation, protection method.

1. INTRODUCTION

Underground cable systems were historically relatively short and installed mostly in populated areas. With advent of HVDC, long underground cable links were started to be installed spanning as long as hundreds of kilometres typically also in rural areas. Until now, lightning was mostly considered from the perspective of overvoltages stressing the cable main insulation and the issue is tackled by insulation coordination and protection with surge arresters. The risk for underground cable damages from lightning strike to ground in proximity of the cables however has not been as widely recognised nor received the same attention.

This study case is about a HVDC link which is located in the middle-south Sweden called SouthWestLink (SWL). It consists of two symmetrical monopoles where, each symmetrical monopole is rated for ±300 kV, 600 MW. The link is implemented as (from north to south) 10 km cable followed by 61 km OHL and followed by 182 km cable installation. The cables of both links were installed in the same trench, see Figure 1. The cable has rather common design for underground cables; stranded compacted aluminium conductor, DC-XLPE insulation system, copper screen wires, aluminium laminate radial water barrier and HDPE sheath. The longitudinal water tightness is secured by swelling materials both in the conductor and at screen wires. The cable system is directly earthed; the joints are earthed locally in the joint bays, the terminations to the earthing grid of the stations. The earthing of the separate symmetrical monopole systems is independent, every system is earthed at each joint bay consecutively, i.e. when one system has earthed joints at a specific joint bay the other system is not and has straight-through joints.

Figure 1 The cable systems during installation.

The cable installation took place during 2013-2014 and sheath testing was performed during after-installation-testing which confirmed sheath integrity at the time. Due to delays in converter project the links were to be taken into operation first in 2019. During the trial operation of link 1 a number of joint failures were encountered after which it was decided to initiate a joint replacement programme. All joints of both cable systems were replaced with improved design 2020. Sheath testing during the replacement programme showed that the sheath was no longer intact. The damages were located outside the joint bays implying that the sheath damages were not related to possible mechanical damages caused by non-careful handling of the cables during joint replacement.

Sheath damages were found at 10 locations along the cable route after approximately 7,5 years during the period January 2013 to June 2020. Each location was most commonly found to have numerous sheath punctures up to 24, most of which were usually limited to a 20-30 m long area, see Figure 2*Figure 2*. However, some could also be found up to about 400 m further away. Few locations were less damaged with few 1-3 punctures. At the locations with numerous punctures it was common that the sheaths of both cable systems were damaged. The damages were not severe enough to immediately damage the cable main insulation system, however these allowed for water intrusion under the sheath. At four locations, lightning-damaged trees were observed at a distance of 10-30 m from the sheath damage location. At these locations the sheath damages were the most severe. In total 7 out of 10 damages occurred in proximity to a forest edge at a distance of about 10 m.

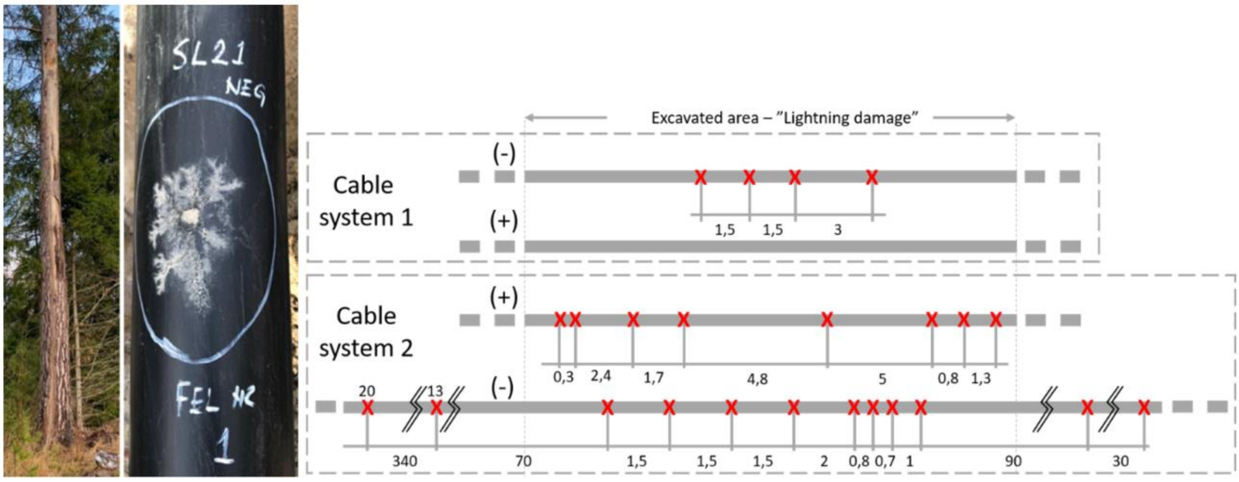

Figure 2 Lightning damaged tree in proximity of damage location (left). One sheath puncture (middle). Schematic illustration of numerous sheath punctures of both cable systems at one damage location, distances between punctures in meters (right).

2. DISSECTIONS

Approximately 10 m long cable piece containing multiple sheath damages was cut out and afterwards dissected in a material laboratory. The observed sheath punctures varied in severity. The puncture severity ranged from only damaged HDPE sheath; larger had damaged sheath and small puncture in Al laminate, see Figure 3; while the most severe case had damages in sheath, Al laminate and even somewhat damaged outer semiconductive layer. The punctures were in radial direction through the sheath. It was also observed that the circumferential location of punctures was aligned with the edge of Al laminate seam. The sheath thickness was measured and was found in agreement with the project requirements. Water intrusion under the sheath was present where Al laminate was punctured however the water penetration along the cable was limited to few decimetres along the cable.

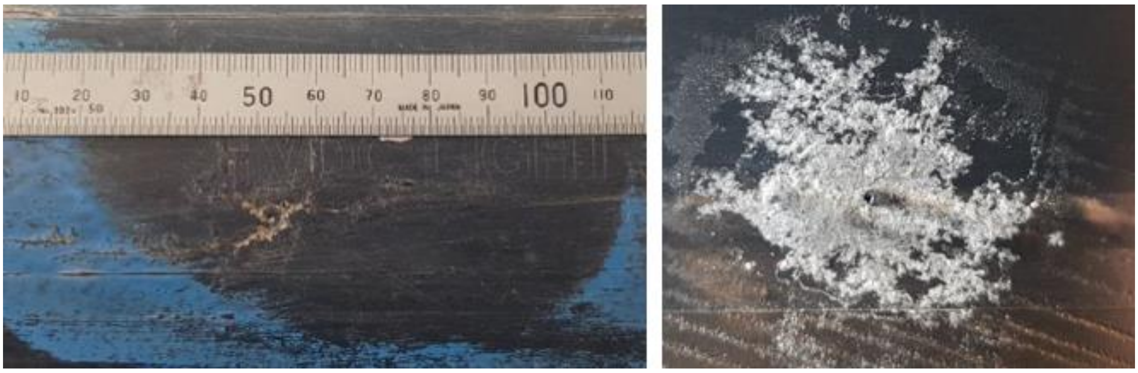

Figure 3 Puncture in the sheath seen from outside (left) and from inside (right).

3. VOLTAGE WITHSTAND TEST ON CABLE SHEATH

Sheath testing on power cables is normally performed with DC voltage during different parts of testing to ensure the sheath integrity. Lightning impulse withstand voltage of the sheath, however is normally not known. The following testing was performed in order to find the actual lightning withstand voltage for these cables which could be used as a reference value in modelling and risk estimation.

Three 1,5 m cable samples from the same spare cable were prepared and used for the sheath withstand test. Impulse test with a short impulse, 1,2/50 μs standard lightning impulse [1] was performed on the cable samples immersed in insulating oil as shown in Figure 4.

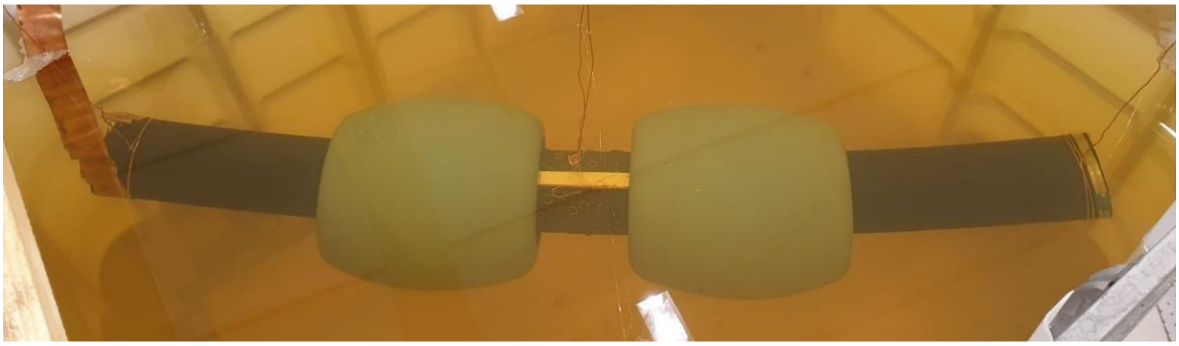

Figure 4 Testing setup. In the picture can be seen: two bluish/grey metallic torus electrodes on the cable sample, brighter stripe in the middle is a small wooden plank for mechanical support for torus electrodes, copper wire connecting test electrode to impulse generator, copper tape connecting screen wires to earth.

The conducting layer of the outer sheath, primarily used for detecting damages in the sheath was scraped off in order to secure insulation along the sheath surface. This was done at each side of a 500 mm centre section of the cable stretching 300 mm towards each cable end. To ensure removal of the conducting layer, a Megger 1 kV dc instrument was used both radially and axially on the surface. As electrode, the 500 mm long centre section of each cable where wrapped with aluminium foil and copper wire, ensuring good conductive properties to the sheath. Electrode and electrode ends were covered with self-amalgamating tape, and to further reduce the field strength between the electrode and the area with the removed conductive layer, two metallic torus electrodes were placed on the cable covering the edge of the test electrode.

Initial voltage of 20 kV was gradually increased in steps of 4 kV up to 100 kV after that in steps of 5 kV until breakdown. The test results showed that the cable sheath was punctured at a voltage amplitude between 115-140 kV.

For all test samples the area of penetration occurred some centimetres outside the edge of the energized surface on the outside of the sheath. This was where the conducting layer had been scraped off. This indicates that the unmanipulated sheath can handle slightly higher voltage amplitudes than what was shown in the test results as. The dissection of the test samples showed that the radial location of the puncture did not coincide with the seam of aluminium laminate, but in two of the three cases the puncture occurred at similar location where the laminate had a wavy structure, Figure 5.

The irregularities due to sheath scrapping and small deformations of aluminium laminate causes local increase of electric field, however such conditions are considered to reflect the actual conditions in field. Considering the breakdown voltage stated above and sheath thickness of 4,5 mm the effective lightning breakdown field strength of the sheath was found to be ca 25-31 kV/mm.

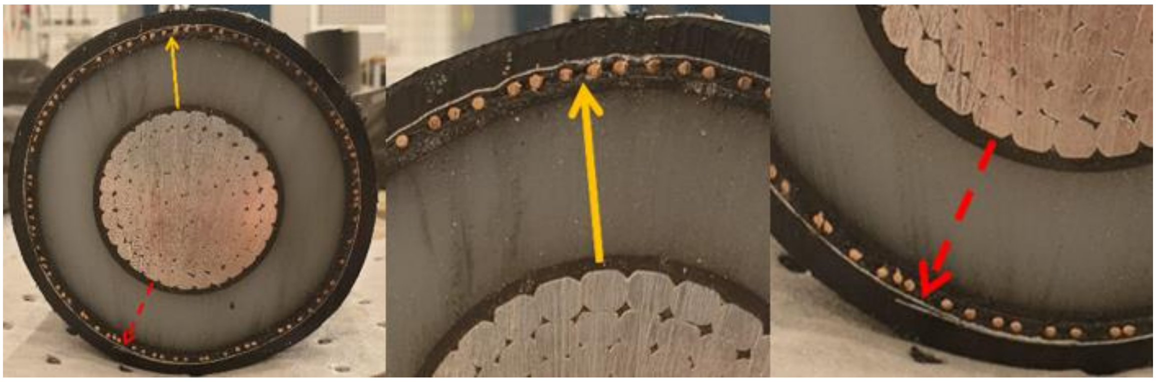

Figure 5 Cross section of cable. Red dashed line indicates the aluminium laminate seam. The yellow arrow indicates the location of puncture which also coincide with the wavy structure of the laminate.

4. METHOD FOR RISK ESTIMATION

The risk of damage to the cable sheath insulation can be assessed by comparing calculated electric field stress in the sheath arising during a nearby lightning strike to the estimated dielectric strength of the sheath. However, the resulting stress is strongly dependent on the lightning current amplitude, soil resistivity and distance between the lightning strike and the cable. This can be taken into account by performing a series of electric field calculations where all parameters are varied. In combination with a representative distribution of ground strike current amplitudes and frequency of occurrence, results of such field calculations can finally be used to estimate the risk of sheath damage from nearby lightning strikes. The different steps are described in the following sections.

Lightning statistics

Lightning current data has been retrieved from the national meteorological and hydrological institute, which, for many years has continuously registered lightning activity throughout Sweden. For each detected strike, information about time, current amplitude, polarity, geographical location, etc. is saved. According to [2], the median positioning error of discharges during normal operation of the measuring system should be less than 500 m. Further, during normal operation, the system is expected to register at least 90% of occurring ground flashes with an amplitude of ≥5 kA. For individual discharges, the detection rate may be lower.

For the case studies presented in this paper, the lightning data is limited to ground strikes within an area corresponding to a 10 km wide corridor along the cable section of SWL. A summary of the data received for the period January 2013 to June 2020, corresponding to the period in which the cables have been laid, is presented in Table I. The average number of ground strikes within the SWL corridor is estimated at 0,59 per km^2 and year. A cumulative distribution of registered currents is shown in Figure 6.

Table I Summary of recorded lightning strikes to ground within the 10 km wide corridor along SWL during the period January 2013 to June 2020.

		Negative	**Positive**	**Total**
Number of strikes		7280	1235	8515
Number of strikes per km^2 and year		0,50	0,085	0,59
Amplitude (kA)	Mean	13,0	16,6	13,6
	Median	10,0	11,0	10,0
	10 %	24	32	25
	1 %	62	101	72
	Max	220	382	382

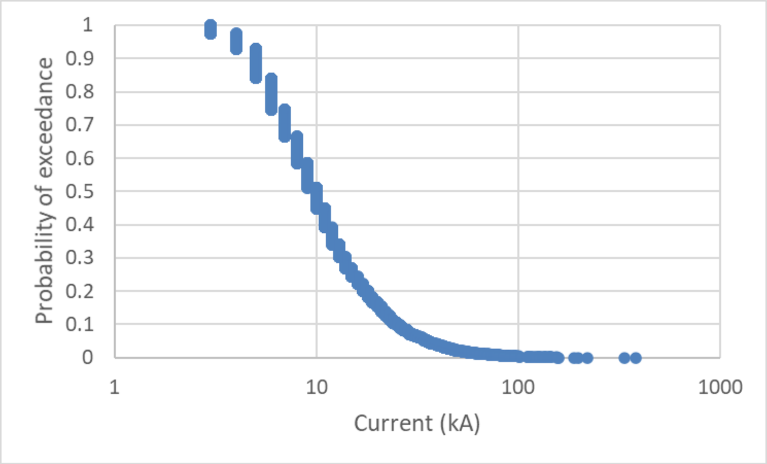

Figure 6 Distribution of lightning strikes to ground within the 10 km wide corridor along SWL during the period January 2013 to June 2020.

Electric field calculations

3D electric field calculations allow for estimation of the electric stress on the cable sheath insulation that arises as a result of ground potential rise in connection with a nearby lightning strike [3]. The effect of soil ionization can be included in the calculations, as well as the effect of any accompanying parallel cables or bare conductors. To estimate the maximum voltage stress on the cable sheath insulation, it is therefore sufficient to calculate the ground potential next to the cable when the lightning current reaches its peak value, which normally occurs within 5-10 microseconds after the strike [3].

In order to calculate the ground potential, the ionized soil around the striking location first needs to be approximated by a hemisphere whose radius is calculated by assuming that the ionization ceases when the electric field strength has decreased to a critical value, which depends on the soil properties.
For the case studies presented in this paper, electric field calculations were performed using FEM. Maximum stresses in the sheath insulation were determined for different installation conditions, i.e. cable trench cross sections and soil resistivities. In the model, cables are represented by tubes of insulating material, having a thickness corresponding to the cable sheath insulation and an inner surface specified to be at ground potential. Shield wires are modelled as ideal conductors at ground potential. The injected lightning current is represented by specifying a selected current density on the surface of a small hemisphere placed at the ground surface. The ionized soil region, which is represented by a hemisphere around the strike location, is modelled by a reduced soil resistivity (7% of the surrounding soil resistivity based on [4]). The size of the ionized region is estimated according to [5], using a critical field strength of 300 kV/m. In Figure 7 the small hemisphere is the current injection location while the large hemisphere is the ionised soil region.

In reality, the cable screen is not perfectly circular, and deviations in insulation thickness as well as presence of sharp conductive protrusions may provide significant local field enhancements. The impact of the aluminium laminate seam at the inside of the sheath was thus considered by 2D electric field calculations where the geometry was modelled in detailed. Results indicate local field enhancements in the order of 1,4-2 times the background field.

Insulation strength

Results from investigations of breakdown voltages of typical cable sheaths are available in [6]. For relevant sheath thicknesses, the breakdown voltage at lightning impulse is approximately 50 kV/mm. The effective breakdown strength including field enhancement effects found from the testing was 25-31 kV/mm. For the study cases presented in this paper, the sheath insulation is assumed to have a breakdown strength of 30 kV/mm, i.e. approximately 15-22 kV/mm if the derived field enhancement factors are applied.

Risk estimation

Interpolation of results of field calculations allow for estimating minimum distances where lightning strikes of different magnitude may cause breakdown of the sheath insulation, see example for SWL in Table II.

Table II Shortest distance where lightning currents are expected to result in damage to the sheath insulation.

Current amplitude (kA)	Distance from nearest cable (m)
3	3
10	9
30	17
100	40

Using the distances of Table II, a corresponding exposed area (where a strike is likely to result in sheath damage) can be determined. For each distance, a contribution to the total number of sheath damages is calculated by multiplying the number of strikes within the additional exposed area by the probability of a current amplitude exceeding the given value. Finally, the total number of expected sheath damages is calculated by summing the contributions for all distances. The result is an estimate of number of sheath damages per cable route kilometre and year.

5. PROTECTION METHODS AND RESULTS

Case study - SWL

The soil resistivity along the SWL cable route is typically rather high (1000-3000 Ωm), but to cover all soil conditions, the analysis was performed for soil resistivity values of 100, 1000 and 10000 Ωm. Field calculations were carried out for different configurations, including the existing layout with four cables without any shield wires (Case 0) and two different options for improved protection where shield wires are introduced. Since the SWL is in operation, shield wires cannot be installed closer than a few meters from the existing cables. In Case 1, one protective shield wire is introduced on each side of the cable route; placed 2 m from the outer cable and at a depth of 0,5 m. In Case 2, three protective shield wires are introduced on each side (one at 1,5 m and two at 2 m from the outer cable, at depths of 1,5 m, 1,5 m and 0,5 m).

Figure 7 show examples of equipotential line plots for the three different study cases. The results were obtained for a lightning current amplitude of 100 kA, injected at a distance of 10 m from the nearest cable, and a soil resistivity of 1000 Ωm.

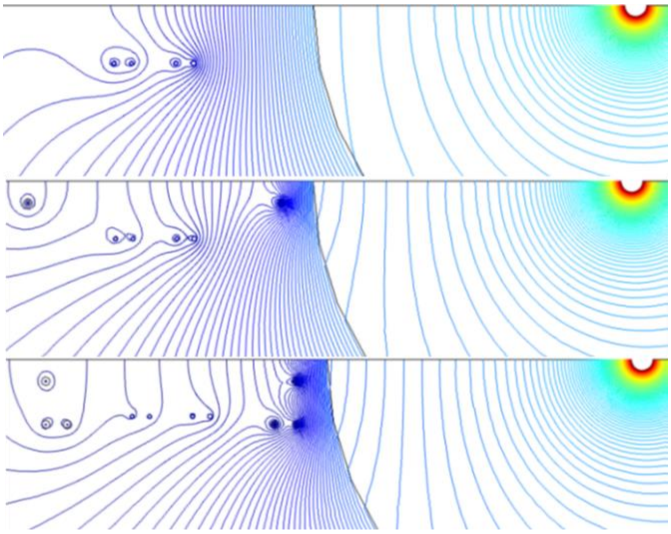

Figure 7 Geometries and equipotential lines of Case 0 (top), Case 1 (middle) and Case 2 (bottom).

Maximum electric field stress in the sheath insulation for Case 0 were determined for combinations of lightning current amplitudes (3, 10, 30 and 100 kA), soil resistivity values (100, 1000 and 10000 Ωm) and distances between the cable and lighting strike (0-40 m). From the results, a minimum distance from the nearest cable where a strike can be expected to cause damage (risk distance), could be estimated. Together with ground strike density (0,59 per km^2 and year), lighting current distribution and total cable route length, an estimate of the number of sheath damages could found, see Table III.

Table III Estimated of number of expected sheath damages per year on the SWL.

Risk distance (m)	Corresponding lightning current (kA)	Probability to exceed current	Total risk distance (both directions from cable route center) (m)	Number of expected sheath damages per year
3	3	1	8	0,8
9	10	0,5	20	0,6
17	30	0,07	36	0,11
40	100	0,004	82	0,018
All	**-**	-	-	**1,53**

The calculated expected sheath damages per year of 1,53 correspond well with the observed 10 damaged locations during 7,5 years, i.e. 10/7,5 = 1,33.

The effects of countermeasures (Case 1 and 2) were estimated by identifying current amplitudes where calculated field strengths matched stresses of Case 0. This is illustrated in Table IV, where similar field strengths are obtained for Case 0/30 kA, Case 2/80 kA and Case 2/100 kA. Applying the different probabilities of exceedance, the relative improvement of protection according to Case 1 and 2 could be estimated at 76 % and 95 %, respectively. Considering the cable route length (ca 200 km), the mean time between failure (MTBF) of the sheath is estimated as shown in Table V.

Table IV Calculated maximum electric field strength in sheath insulation (absolute values including field enhancement factor) at lightning strike 10 m from the nearest cable. Values exceeding 30 kV/mm marked by red.

Lightning current (kA)	Soil resistivity (Ωm)	Radii of ionized hemisphere (m)	Electric field stress (kV/mm)		
			Case 0	**Case 1**	**Case 2**
100	10000	23			50
100	1000	7,3			66
100	100	2,3			13
80	10000	17,1		62	
80	1000	5,4		58	
80	100	1,7		15,5	
30	10000	12,6	62		
30	1000	4	50		
30	100	1,3	20		

Table V Estimated reduction of risk of failure and corresponding MTBF.

Study case	Risk reduction (%)	MTBF (years)
Case 0 (existing)	0	0,5-1
Case 1	76	2-4
Case 2	95	9-18

Requirements on shield wires

In the event of a lightning strike to ground, the lightning current will be distributed in different directions in the soil. Any shield wires in the vicinity will divert part of the current and thereby reduce the ground potential. The magnitude of the current will depend on the lightning current amplitude, the distance from the impact site, the ground resistivity, the number of shield wires, etc. Considering associated temperature rise, a copper conductor with cross section of 16 mm^2 is sufficient to handle the complete specific energy of a lighting current impulse associated with LPL I (200 kA) according to [7]. Since only a portion of the total lightning current is expected to flow in the wire, the estimated cross section is considered conservative. Thus, in practice, requirements on cross section area should be based on mechanical aspects.

6. SELECTION OF PROTECTION

Selection of the suitable configuration of the shield wire for existing cable systems depends of course on several factors such as the expected MTBF, installation costs, planned sheath testing interval and also installation complexity and risks. For example configuration in Case 2 gives MTBF ca 20, however requires 3 times amount of shield wires in comparison to configuration Case 1. Configuration in Case 2 also requires installation at the depth the same as the existing power cables. Nevertheless the installation would be performed at ca 2 m distance from the outer cable the risk of damaging the cables by digging is considered rather high and this would eventually require shutting down the links during the installation. Considering the reasoning above and the fact that the common sheath testing interval is ca 5 years [8] makes Case 1 configuration also a viable option.

For new cable installations the shield wires laid in the same cable trench can provide suitable protection. The configuration can be selected such that it fulfils the required protection and also allows for practical installation. For example shield wires can be laid in the corners of the trench and afterwards covered with the thermal backfill constituting the cable bed. Afterwards the remaining shield wires can be installed in the trench corners above the thermal backfill layer. To protect the cables installed in PE-tubes shield wires could be installed on the outside of PE-tubes. Risk estimation using the presented method shows that such configuration gives good protection against lightning strike.

7. DISCUSSION AND CONCLUSSIONS

Starting with the observations from the field there was an indication that lightning strike to ground could be the possible explanation to the observed damages, i.e. presence of the lightning damaged trees in proximity, also the fact that the both cable systems were damaged at the same location despite independent earthing systems. Laboratory testing produced punctures of a similar nature as observed in the dissected cable from the field. The sheath breakdown strength obtained from the laboratory testing with lightning impulse corresponds with the breakdown strength used in the model used for the analysis and risk estimation. And finally, the calculated expected sheath damages correspond well with the observed amount of damages.

Until now, lightning was mostly considered from the perspective of overvoltages stressing the cable main insulation and the issue is tackled by insulation coordination and protection with surge arresters. The risk for underground cable damages from lightning strike to ground in proximity of the cables however has not been as widely recognised nor received the same attention. The risk of cable damage from the direct lightning strike could be found documented in literature, however these articles focused on communication cables e.g. [9]. Some more recent papers investigated such risks even for medium [10] and high voltage cables [6]. Papers [9] and [10] also tackle the topic of the possible protection schemes in the form of the shield wires installed in parallel with the underground cables. Considering all the facts it is concluded that the most probable cause of the observed damages is caused by the lightning strike to ground in proximity of the power cables. The lightning strike issue is found to be particularly problematic in Sweden and other Nordic countries due to the fact that ground electrical resistivity is generally high here due to presence of bedrock of granite and gneiss. As a comparison typical soil resistivities are in the range of 100-500 Ωm [9], however in Sweden the majority of the land exhibits resistivities which are above 2500 Ωm [11]. It is possible however to achieve an adequate protection using the configuration of the shield wires even in such difficult conditions as found in Sweden.

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