

# Cable Protection against Earth Potential Rise due to Lightning on a Nearby Tall Object

U. S. Gudmundsdottir, C. F. Mieritz

**Abstract--** When a lightning discharge strikes a tall object, the lightning current is driven into the grounding system. Due to the impedances to remote earth, the current injection will result in an increased potential of the surrounding soil during the impact of the strike. This earth potential rise (EPR) will have an impact on buried cable installations in proximity of the grounding system, and will in severe cases damage the cables.

The present paper covers an analysis of the potential rise across the cable outer sheath, when buried in proximity of a grounding system subjected to lightning currents.

**Keywords:** EPR, lightning, cable protection, Earth Continuity Conductor, Underground Cable

## I. INTRODUCTION

WHEN undergrounding large amount of cable systems, the Danish Transmission System Operator, Energinet.dk, has been faced with the problem of having tall objects, such as wind turbines and overhead line (OHL) poles, placed less than 50 m away from cable tracks.

When tall objects are placed in an otherwise open area, this will increase the probability of a lightning strike on that object. A lightning strike will cause potential rise in the soil around impact [1]. A critical high EPR can cause damage of the cables outer covering, due to the potential difference in the soil around the cable and on the cable screen. The result is several small holes in the outer covering of the HV cable, which with time can cause corrosion in the cable screen.

In this paper, reduction of EPR around an underground HV cable, due to lightning strikes on a nearby tall object is discussed. A Finite Element Model (FEM) is implemented in order to analyse the spread of the voltage rise due to the current injection from the lightning stroke. The minimum distance between the tall object and the HV cable, in order for the cable not to experience problems due to EPR is given. For cases where this distance cannot be increased, two solutions for protecting the cable outer covering are analysed.

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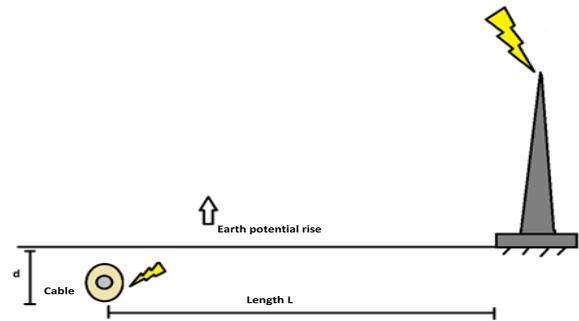


Fig. 1 Illustration of the EPR around a cable, due to a lightning strike in a nearby tall object. The cable is buried  $L$  meters from the tall object, and in a depth of  $d$  m.

## II. GEOMETRICAL PROPERTIES

For studies of EPR due to lightning strokes near an underground cable, there are three important geometries;

- 1) The tall object such as an onshore wind turbine.
- 2) The cable.
- 3) The cable trench including all parallel cables and other nearby conductors.

The lightning is simulated based on IEC 62305, with a first Return Stroke (FRS) of 200 kA at 25 kHz (having a front time of appr. 40  $\mu$ s) and Subsequent Stroke (SSS) of 50 kA at 1 MHz (having a front time of appr. 1  $\mu$ s) for Lightning Protection Level 1 (LPL1) [2].

### A. Tall object

When analysing EPR due to a lightning stroke on a tall object, it is crucial to include correct modeling of both the object and the buried foundation. A tall object, with a large deeply buried foundation, including a ring electrode, such as a tall windmill, will cause much less EPR problems to nearby cables, than for example a small foundation of an OHL pole, without any ring electrode.

An example of this difference can be seen in Fig. 3, where the EPR around a foundation, due to a 200 kA first return lightning stroke, is compared for following three cases:

- OHL pole with a typical plate fundament of steel reinforced concrete, of height 2.77 m and surface area of 10x11.5 m.
- Gravity foundation for a wind mill. This foundation is of 15 m in diameter in the ground and of height 3 m.
- Gravity foundation with a ring electrode. This foundation is a typical windmill foundation, where the grounding system is improved by adding a ring electrode. This foundation is 5m deeper in the ground, than the gravity foundation without a ring electrode.

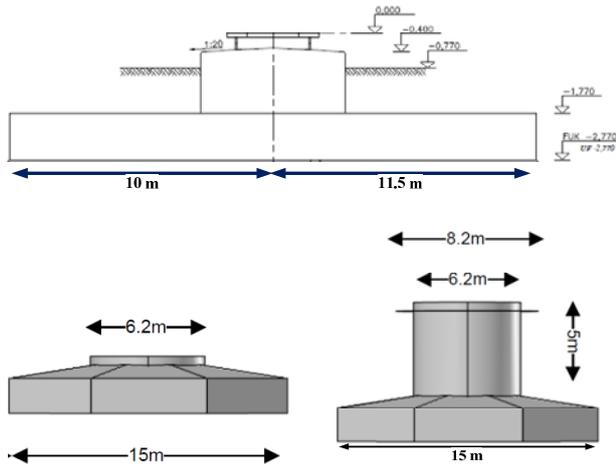


Fig. 2 Three different types of foundation. Top: Overhead line foundation of steel reinforced concrete. Left: Gravity foundation reinforced with ring concrete. Right: Gravity foundation with ring electrode.

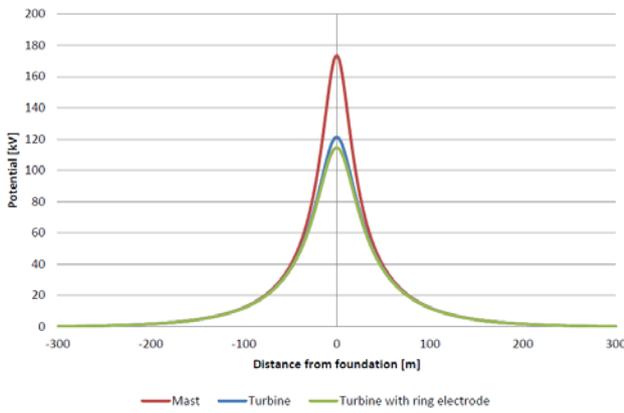


Fig. 3 EPR around three different types of foundation.

Due to material and size, the EPR around the gravity foundation is much less than around an OHL foundation. Even though the peak EPR is less, cable at approximately 50 m away will experience the same EPR, around 60 kV.

### B. High voltage cable

For studying the effect of EPR on a high voltage cable, due to a lightning stroke on a tall object, the voltage across the cable outer sheath is of an importance. The cable screen is grounded at approximately every 3-4 km. This can cause small holes in the outer sheath when the EPR is high close to the cable.

The EPR is plotted for a cable modeled with the metal screen kept at earth potential.

As only the voltage difference across the cables outer sheath is of interest, it is possible to disregard the voltage variation on the cable screen.

Normally a PE outer sheath can withstand an electric field of approximately 4.7 kV/mm. Therefore, for a PE outer sheath of 3-1 mm, a non-destructive EPR can reach maximum of 14-47 kV at the outer side of the cable.

### C. Cable trench

The soil resistivity in the ground between the tall object and the HV cable is of great importance for correct EPR calculations. EPR can be calculated using (1), where  $\rho$  is the soil resistivity,  $x$  is the distance from the tall object and  $I$  is the lightning current at ground surface.

$$EPR(x) = \int_{r_1}^{r_2} \rho \frac{1}{2\pi x^2} dx \cdot I \quad (1)$$

Therefore; the lower the resistivity, the lower the EPR. The difference in EPR can be more than 3 times looking at soil resistivity from 50  $\Omega$ m to 150  $\Omega$ m, as shown in Fig. 5.

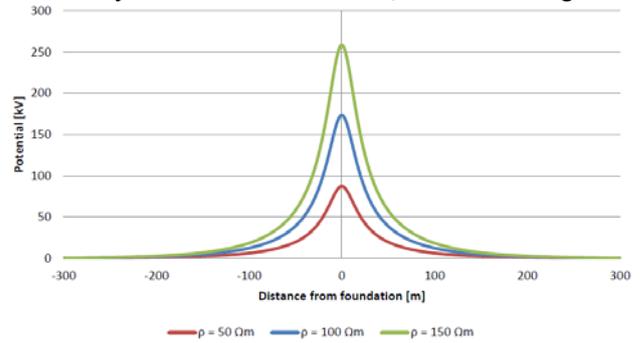


Fig. 5 EPR around an OHL foundation for different soil resistivity

Soil resistivity can vary from 30  $\Omega$ m for a very moist soil to 1000  $\Omega$ m for dry gravel [3]. Typical soil resistivity in Denmark is 100-150  $\Omega$ m.

## III. CASE STUDY

The EPR due to an OHL pole close to an underground HVDC cable line in Denmark is studied in the Finite Element program (FEM) Comsol Multiphysics, in order to find ways to protect the cable from lightning strokes on nearby tall objects. The study is performed in the time domain where the impedance boundary condition is applied on the boundary of the grounding system. A voltage in time domain is applied to the edge of the OHL pole or turbine foundation intersecting the upper boundary foundation. This voltage is then varied in time constants and amplitude such that the current into the grounding system (found by integrating the current density along the earthed surfaces of the analysis volume) matches the first and subsequent stroke currents of 200 kA with a 4 $\mu$ s front time and 50 kA with a 1 $\mu$ s front time, respectively.

The soil resistivity in the area of the cable line is 100  $\Omega$ m. The cable has a 5.35mm thick PE outer sheath, which can withstand an EPR of 25 kV. According to Fig. 5, the cable must be placed at least 65 m away from the OHL pole if no protection measure is taken. Due to terrain and trench plans, it is not possible to keep the necessary 65 m distance. It is therefore of interest to find alternative solutions for lowering the EPR. There are two options, improving the foundation grounding, or adding an ECC to the cable system, in order to pick up the EPR from the lightning current.

### A. Parallel ECC

The parallel ECC is put in parallel to the HV Cable with distances of 10 m, 5 m, 0.1 m, -0.9 m and -5 m, as illustrated in Figure 6.

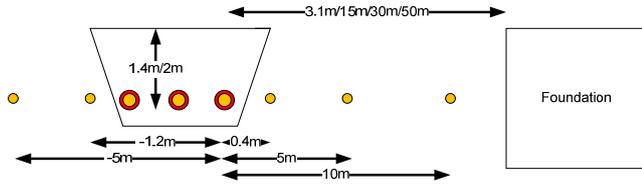


Fig. 6 Installation of an ECC for lowering EPR

The radius of the modelled ECC is 25 mm giving a cross-sectional area of approximately 2000 mm<sup>2</sup>, which is much larger than the 95 mm<sup>2</sup> or 120 mm<sup>2</sup> that would be used. The increase of radius is necessary in order to mesh the conductor in Comsol Multiphysics. To compensate for this major difference, the conductivity of the copper conductor is lowered by the ratio between the cross sectional areas, giving an overall resistance of the modelled 2000mm<sup>2</sup> ECC similar to the 95 mm<sup>2</sup> copper wire.

$$\sigma_{compensated} = \frac{A_{95}}{A_{2000}} \cdot \sigma_{Copper} = 2.83 \cdot 10^6 \text{ S/m} \quad (2)$$

Where  $\sigma$  is the conductivity and A is the surface area of the conductor.

The evaluation of the parallel conductor is divided into three studies;

- Distance between HV cable and the ECC.
- The length of the ECC, and distance between HV cable and foundation.
- Multiple parallel conductors.

The LPL1 for first return stroke in the frequency domain has the same peak potential as the first return stroke in the time domain, and a much larger peak value compared to the subsequent stroke. Therefore, the model is solved with 200 kA at 25 kHz (LPL1) as input current in the frequency domain. Furthermore, the evaluation is done by considering the potential distribution along the length of the cable closest to the foundation, at the surface facing the foundation.

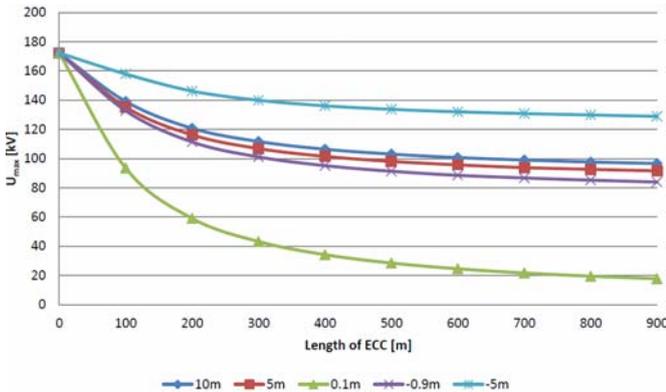


Fig. 7 Maximum potential vs. position and length of ECC, for a distance of 15 m between HV cable and foundation, and at a burial depth of 1.4 m.

In Fig. 7 the EPR for different distances between the HV cable and the ECC is studied. Significantly lower peak voltages correspond to the shortest distance between the ECC and the cable. The optimum protection is by having the ECC 0.1 m from the HV cable, facing the direction of the pole foundation.

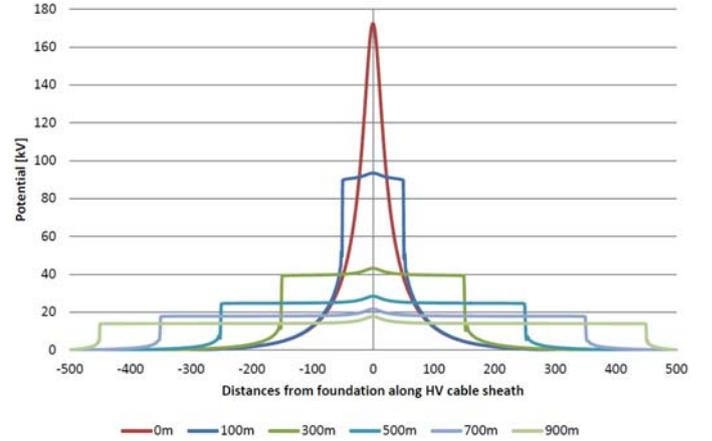


Fig. 8 Potential along the HV cable metal screen for varied lengths of ECC. The cable is 15 m from the foundation and ECC is 0.1 m from the cable.

In Fig. 8, the potential for “0m” corresponds to the original situation without any protection and might be recognized with Fig. 3-Fig 5, for foundation of an OHL pole and soil resistivity of 100  $\Omega$ m.

The maximum potential on the outer sheath of the HV cable without protection is 172 kV. By applying the parallel conductor, the potential on the cable outer sheath is decreased. The potential decrease becomes larger for increasing length of conductor, until a certain length where the effect of adding extra 100 m of conductor becomes very low. The potential on the cable outer sheath is decreased to 25 kV by placing a 600 m long ECC 0.1 m from the HV cable. From Fig. 8, it is seen that increasing the length of the ECC to 700 m or 900 m lowers the potential on the cable sheath to less than 20 kV which is below the specified breakdown voltage of 25 kV of the cable sheath. However, the use of ECC's longer than 900 m located 0.1 m from the cable is not suitable for the cable trace, due to asymmetry between the three cables, [4].

The results shown in Fig. 8, are for a cable placed 15 m from the foundation of the tall object. Table I sums the maximum potential for the different configurations shown in Fig. 6.

TABLE I  
MAXIMUM POTENTIAL [kV] VERSUS LENGTH OF CONDUCTOR AND DISTANCE BETWEEN HV CABLE AND FOUNDATION. THE BURIAL DEPTH AND DISTANCE BETWEEN CABLE AND CONDUCTOR IS 1.4 M AND 0.1 M, RESPECTIVELY.

Length, ECC [m]	0	100	200	300	400	500	600	700	800	900
Distance [m]	$U_{max}$ [kV]									
3.1	690	190	119	90	73	63	56	52	48	45
15	172	93	59	43	34	28	25	22	19	18
30	79	56	38	28	22	18	-	-	-	-
50	40	33	24	18	15	12	-	-	-	-

For protecting the cable from lightning stroke to a tall object, it is recommended to keep a minimum distance of 15

m between the HV cable and the foundation. In the case where increasing the distances to 15 m is not an option, the single ECC placed 0.1 m from the HV cable might not be a proper solution because of the problems with having parallel conductors longer than 900 m. Furthermore, placing only one ECC will not protect all three cables, as shown in Fig. 9.

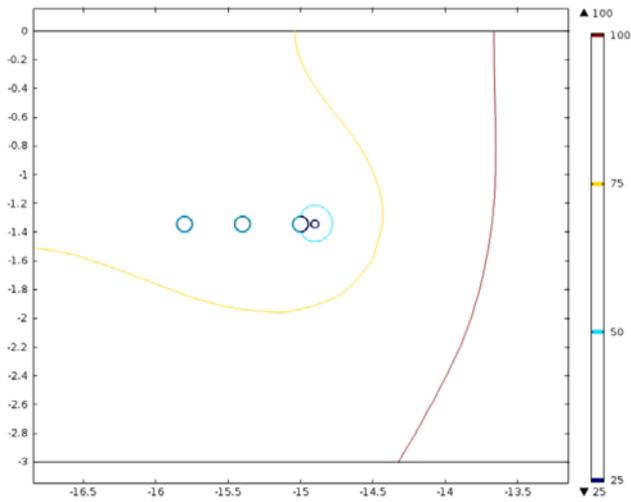


Fig. 9 EPR [kV] for a single 500 m long ECC traced at 0.1 m from the HV cable with a distance of 15 m from the foundation.

When considering use of multiple ECC's, the burial depth is kept at 1.4 m, and the distance from the HV cable to the foundation of the tall object is tested at 3.1 m and 15 m for two ECC's located at 0.1 m and -0.9 m from the HV cable, and at -0.1 and -0.7 m from the HV cable.

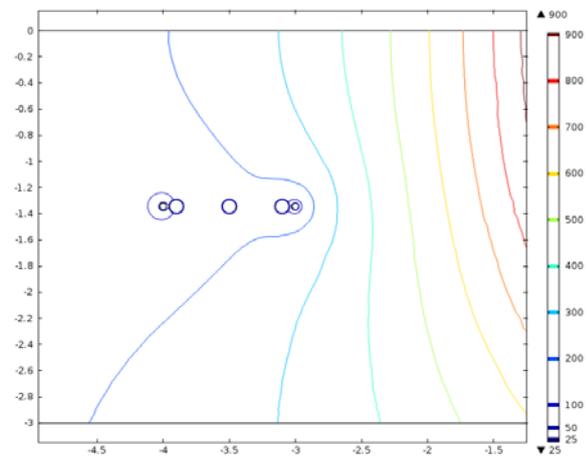


Fig. 10 Potential [kV] along the HV cable metal screen for 500 m long ECC traced at 0.1 m and -0.9 m from the HV cable with a distance of 3.1 m from the foundation.

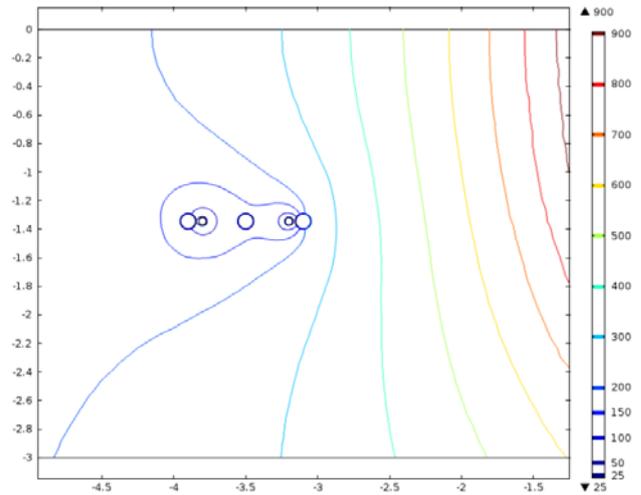


Fig. 11 Potential [kV] along the HV cable metal screen for 500 m long ECC traced at -0.1 m and -0.7 m from the HV cable with a distance of 3.1 m from the foundation.

From Fig. 10 and Fig. 11, it is not possible to reduce the EPR to 25 kV on the outer sheath of the cable, when the distance of the cable from the foundation is only 3.1 m. For a distance of 15 m between the foundation and the HV cable, the results are shown in Fig. 12 and Fig. 13.

It is important to note, that the ECC only controls the potential distribution in immediate vicinity of the cable, such that one side of the cable might be protected by the ECC, whereas a puncture can occur at the opposite side. When using two ECC's, it is better to place them in between the three phase conductors, instead of on the outside of the two outermost conductors. With two ECC's the voltage is still reduced by increasing the distance from the cable to the foundation, and a distance of minimum 15 m is recommended.

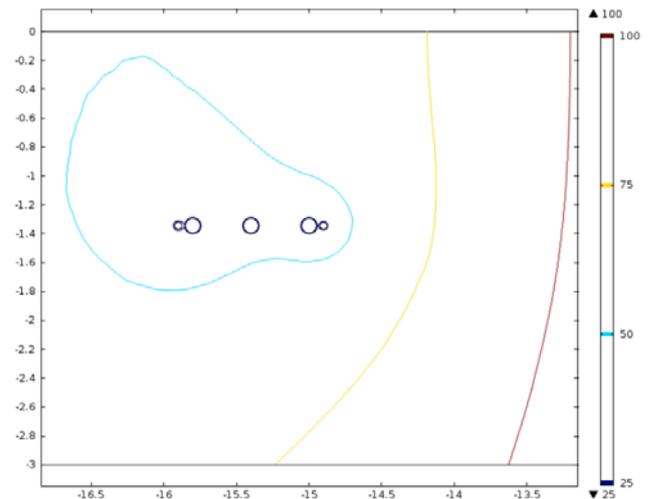


Fig. 12 Potential [kV] along the HV cable metal screen for 500 m long ECC traced at 0.1 m and -0.9 m from the HV cable with a distance of 15 m from the foundation.

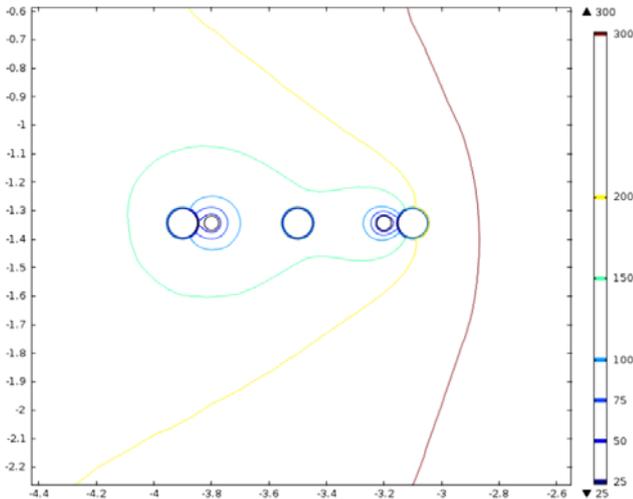


Fig. 13 Potential [kV] along the HV cable metal screen for 500 m long ECC traced at -0.1 m and -0.7 m from the HV cable with a distance of 15 m from the foundation.

Generally the use of parallel ECC's has a significant impact on the reduction of the potential, and is thereby a good solution for protecting the HV cables against the EPR due to a lightning strike on a nearby tall object.

### B. Improved foundation grounding

The aim by using improved foundation grounding is to make a better connection to ground, in opposite direction from the cable in question. This can move the highest potential away from the cable as illustrated in Fig. 14. The additional grounding system consists of seven conductors with a cross sectional area and conductivity corresponding to a 95 mm<sup>2</sup> copper conductor.

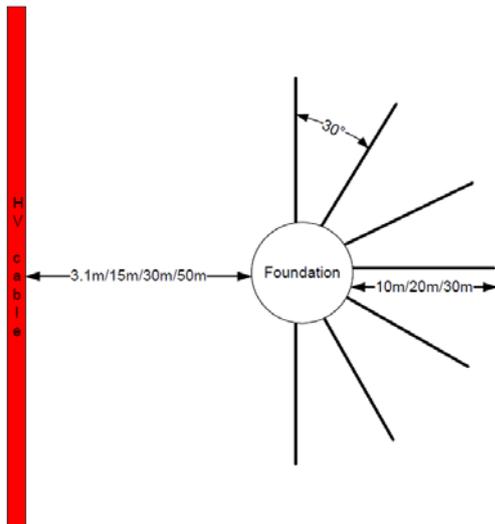


Fig. 14 Illustration of additional grounding system to the foundation.

The results of adding extra earthing system to the foundation are shown in Fig. 15 – Fig. 17, where three different lengths of copper conductor are used; 10 m, 20 m and 30 m.

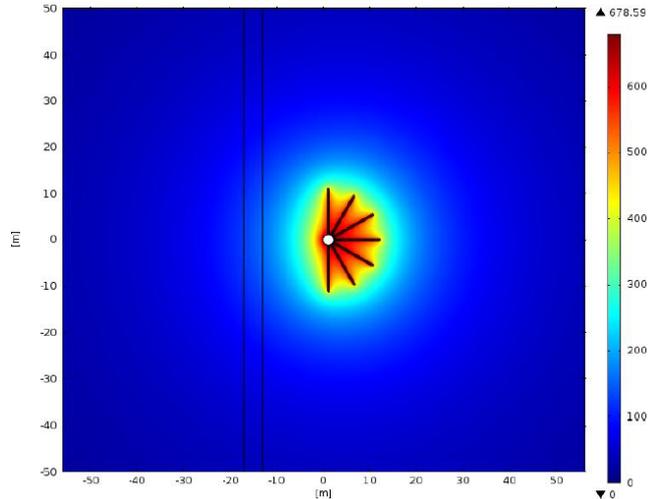


Fig. 15 Illustration of the potential [kV] for additional earthing system on the tall objects foundation, using 10 m copper conductors.

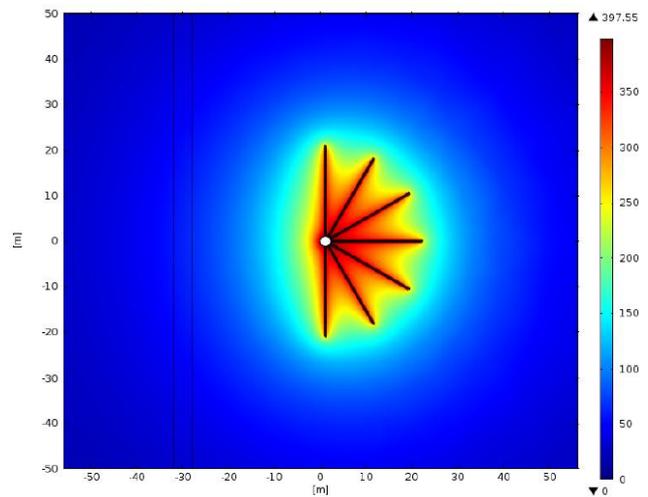


Fig. 16 Illustration of the potential [kV] for additional earthing system on the tall objects foundation, using 20 m copper conductors.

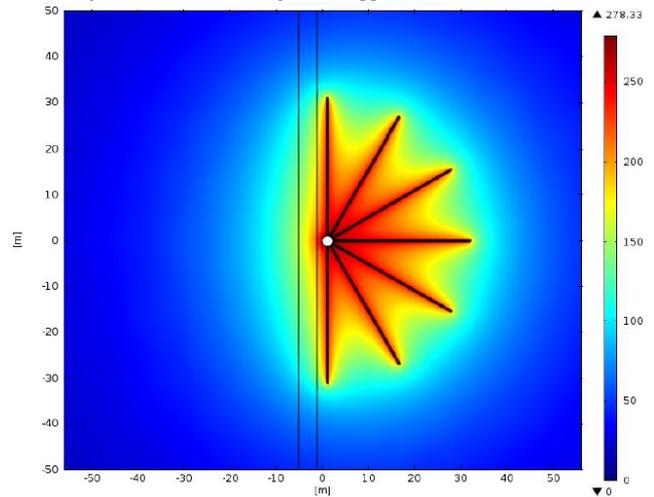


Fig. 17 Illustration of the potential [kV] for additional earthing system on the tall objects foundation, using 30 m copper conductors.

From Fig. 15- Fig. 17 it can be seen that the potential at the foundation, when injecting 200 kA LPL1 lightning current, decreases from 679 kV to 278 kV by the length of the copper conductors from 10 m to 30 m. This is due to the larger contact area with the surrounding soil, and hence an easier dissipation of the lightning current. The decrease of potential at the foundation does also have an impact on the potential at the HV cable outer sheath, which becomes lower

as illustrated in Table II.

TABLE II  
MAXIMUM POTENTIAL ALONG THE HV CABLE OUTER SHEATH FOR  
DIFFERENT LENGTHS OF COPPER CONDUCTORS AND DIFFERENT DISTANCE  
BETWEEN HV CABLE AND FOUNDATION

Distance, HV cable to foundation [m]	3.1	15	30	50
length of extra conductors [m]	U <sub>max</sub> [kV]			
0	690	172	79	40
10	374	140	71	37
20	242	112	62	34
30	180	93	54	31

It is evident from the above results, that the length of the additional grounding wires has an impact on lowering the maximum potential on the cable outer sheath. It is also evident, that improving foundation grounding cannot be used as a standalone solution, as the EPR is above 25 kV even at the cable outer sheath for 30 m long grounding wires, with 50 m distance between the HV cable and the foundation.

#### IV. CONCLUSION

The paper presents reduction of Earth Potential Rise (EPR) around an underground HV cable, due to lightning strikes on a nearby tall object. It is furthermore shown how the distance between the cable and the foundation of the tall object is crucial, and that a HV cable must be placed with a minimum distance of 15 m from the tall object, in order to be protected. Without any protection of the HV cable, this distance must be at least 65 m. The type of foundation is also relevant for the EPR at the outer sheath of the HV cable. A lightning stroke on a large wind turbine fundament causes less EPR problems compared to a smaller concrete OHL pole foundation. The voltage decrease and current distribution is squeezed together around the small pole foundation, giving the worst case. The larger the foundation, the larger contact area with the soil and this results in a lower EPR.

It is furthermore shown how the actual earth resistivity is important for correct EPR calculations, and a case study is given for study of EPR due to a lightning on a tall OHL pole. LPL1 first return stroke is given as 200 kA at with a front time of 4  $\mu$ s, and it is studied how an ECC with the cable system, and how an extra grounding to the OHL pole, will affect the EPR on the outer covering of the HV cable.

It is not possible only to add additional grounding to the OHL pole foundation, pointing the lightning current away from the cables. It is therefore suggested either to use two ECC's, or to use a combination of ECC and additional foundation grounding. To keep the potential on the HV cable outer sheath below the required 25 kV, all the following solutions must apply:

- The HV cable shall be placed at least 15 m from the OHL pole.
- An ECC of minimum 600 m must be used.
- For protecting all cables, two ECC's must be used.
- The two ECC's should be placed no more than 0.1 m from the inner side of the outer cables.

It is furthermore important to consider the statistics of lightning discharges. In Denmark, a LPL1 first return stroke of 200 kA only occurs in 1% of all incidences, and the median value is around 33 kA [5]. In the risk assessment, the ground flash density should also be considered. In Denmark this is 0.23 flashes per km<sup>2</sup>, per year. These two statistics, should always be taken into account when faced with a tall object close to a HV cable.

As the type and grounding of the conducting material of the cable is not relevant for studies of EPR in the ground around the cable, this study is valuable for arbitrary cables placed close to a tall object. Furthermore, the study can be used to estimate touching voltages of other conducting materials, such as gas or water pipes, due to EPR from a lightning stroke on a nearby tall object. The results can therefore be used to plan protection procedures for cables, water pipes and gas pipes, when OHL's or onshore wind turbines are planned in close proximity.

#### V. REFERENCES

- [1] CIGRE brochure on Earth Potential Rises in Specially Bonded Screen Systems, CIGRE TB 347, June 2008.
- [2] International standard on Protection against lightning, IEC 62305-1, Dec. 2012.
- [3] Fluke guide on Earth Ground Resistance, Fluke Principles, testing methods and applications, 2006.
- [4] Cigre WG 07, "The design of specially bonded cable systems," Electra No 28, SC No 21, pp 55-68, 1973.
- [5] Otrå Danmark A/S, Elnet Peter Benn Thomsen, *NOTAT - Jordtrådsdækning på Eltras 400 kV master (Danish)*, August 2004, 3. edition.