SIMULATION OF EARTH TERMINATION SYSTEMS FOR LIGHTNING PROTECTION SYSTEMS REGARDING STEP VOLTAGES

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Abstract: Earth termination systems are an important part of lightning protection systems. They must be designed such that lightning currents are safely diverted into the ground without generating step voltages on the surface of the soil that would be dangerous to passer-bys. To ensure this, national standards exist in Germany – and assumedly in other countries as well – that describe possible solutions. However, these solutions require costly efforts both in terms of labour and material. Therefore, this contribution examines the effectiveness of several design principles of earth termination systems with the help of finite element computer simulations. Furthermore, a brief overview on considerations of step voltage safety limits is given.

1 INTRODUCTION

The purpose of earth termination systems of lightning protection systems (LPS) is the diversion of lightning currents into the ground. Since soil usually is of poor conductivity, the combination with the high currents associated with lightning strikes tends to lead to high earth potential rises (EPR) at the moment of strike. The decay of the EPR at the entry point into the earth termination system towards an ideal ground leads to potential gradients in the soil. On the surface of the soil, these potential gradients are known as step voltages, which can be dangerous to both humans and livestock if not controlled properly.

In order to provide a sufficient control of step voltages, German national standards provide ways of designing and building earth termination systems. However, these designs require large amounts of conducting material to be buried into the ground which is cost-intensive.

Therefore, it should be examined if alternative, less complex designs are also able to provide sufficient protection. To do this, the 3D computer simulations with the finite element method (FEM) were chosen.

2 CONSIDERATION OF STEP VOLTAGE SAFETY LIMITS

For the evaluation of simulation results, the knowledge of reasonable safety limits for step voltages is crucial. But while effects of direct currents and power-frequency currents to the human body are widely discussed in literature and standards, information on the effects of the special aspects of lightning currents and thereby induced step voltages – i.e. high-amplitude currents with time durations in the microsecond to millisecond range and a foot-to-foot current path in the human body – is available only sparsely.

Therefore, an extensive literature research was conducted. Several different approaches on a theoretical basis led to safety limits in the range of 25-30 kV. Furthermore, Gao et al. conducted 3D FEM simulations of lightning currents passing through the human body on a foot-to-foot current path [1]. The human simulation model, which is based on the so-called *HUGO* model and the Visible Human Project [2] was in turn also successfully verified against Sam's measurements [3].

After comparing all these results against each other, a step voltage limit of 25 kV for a lightning current with a 10/350 µs shape is proposed. This value also coincides with the value in the current draft of the IEC 60479 standard [4] [5].

It must be noted that the term "step voltage" everywhere in this contribution has the meaning of "step body voltage", i.e. the voltage that actually appears across both feet of a human standing on the soil (see also clause 3.2). It can be shown that an unloaded, open loop voltage on the surface is drastically reduced when a human, basically representing a resistive load in the low kilo-ohm range, taps this voltage. The open loop step voltage is, therefore, of no interest here.

3 SIMULATIONS OF STEP VOLTAGES

3.1 General considerations of the simulation models

All simulations presented within this paper were performed on a hemisphere being the considered volume of soil. The radius of the hemisphere was chosen to r = 100 m, and preliminary studies have shown that for all simulated structures so far this radius is big enough to suppress any boundary effects. All curved areas are defined as ground, while the cross section is defined as an electrical insulation, representing the surface of the soil.

For the soil itself, two different conductivities were chosen:

1. σ = 0.001 S/m (ρ = 1000 Ωm) as a worst-case example of poorly conducting soil. This material is defined as not showing any dependence from any other parameter and is called “linear” within this contribution.

2. σ = 0.001 - 0.01 S/m with the exact value depending on the local electrical field in the soil. The transition from the lower to the upper value takes place between *E* = 3 kV/cm and *E* = 5 kV/cm – see **Figure 1**. This is called “non-linear” soil within this contribution and is chosen to model the effect of soil ionisation, which is well-known and described in the existing literature [6] [7].

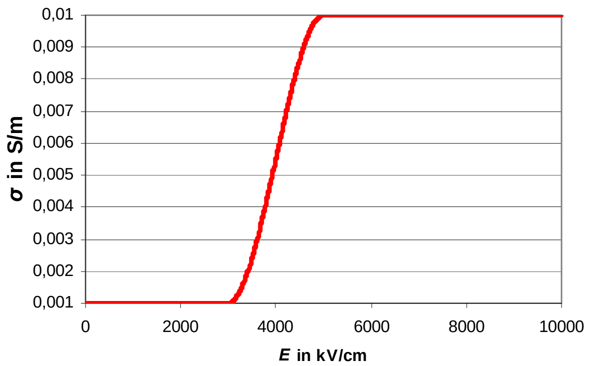

Figure 1: Conductivity vs. electric field strength characteristic of modelled “non-linear” soil.

Several sizes of buildings were investigated so far, but only the results of one size are presented herein: This building is rectangular in shape and is both 10 m long and 10 m wide. The depth of the basement is 2 m. The building is modelled as a simple cut-out from the soil (unless noted otherwise), thus neglecting the influence of basement walls and the like.

Preliminary studies have shown that the highest step voltages will occur along a line that runs from any corner of the building in an angle of 45° towards the building walls. Therefore, all results presented will be given along this line. The radius *r* is measured from the corner of the building to the point under consideration.

3.2 Influence of the human body on the resulting step voltages

It has to be clearly pointed out that a human being standing on the soil will inevitably have an influence on the step voltage distribution. This is because – especially on soil with low conductivity – the conductivity of a human body is much higher than that of the soil. As a simple analogy, the soil can be seen as a voltage source with a high internal resistance, the step voltage as the output of the voltage source and the human body as a low-ohmic load. Hence, the actual voltage drop between a person’s feet will be significantly reduced compared to a measurement with infinitely high resistance of the measuring device or a simple numerical evaluation of a simulation respectively.

Therefore, other preliminary simulative studies were conducted to quantify this influence. Factors between the unaffected and affected step voltages, which depend on the actual conductivity of the soil, were found, and they are also closely related to values that Neuhaus determined by a different analytical approach [8].

All simulation results presented herein are based on a lightning current *I* = 200 kA and have been corrected with the corresponding factors.

3.3 Considered earth termination system designs

The following designs of earth termination systems were considered so far:

3.3.1 Foundation earth electrode For this design, a concrete foundation plate with a thickness of 20 cm and a conductivity of σ = 0.0033 S/m (ρ = 300 Ωm) was modelled in such a way that it fills out the whole footprint of the building. Within this foundation plate, an earth electrode is modelled as follows: rods running along all four sides of the building with a distance of 5 cm both from the base and the walls. The results in terms of step voltage can be seen in **Figure 2**.

3.3.2 Rods One vertical rod was placed at each corner of the building (four rods in total). The rods are connected to each other outside of the soil, and no other earthing electrodes were used in this model. The rods were modelled both in 6 m and 9 m length. Additionally, the 6 m version was modelled with the upper 3 m covered with insulating material. The results can also be seen in Figure 2.

3.3.3 Rings Between one and four rings were modelled in the soil around the building. In every case, the foundation earth electrode as described in section 3.3.1 was also present and connected to the ring structure. The rings were rectangular in shape like the building, placed at distances of 1 m, 4 m, 7 m and 10 m from the building and were buried 0.5 m, 1 m, 1.5 m and 2 m deep respectively. The radii at the corners were chosen to 1 cm. Results of these simuoations are given in **Figure 3**.

3.4 Discussion of simulation results

The simulated step voltages show some remarkable results. First of all, it can be clearly seen that the consideration of soil ionisation leads to lower step voltages. This effect is more pronounced when the conductors of the earth termination system are close to the surface of the soil, i.e. not buried deeply and also if the total length of the conductors of the earth termination system is small. This is, as previous investigations have shown, because soil ionisation usually only takes place within a very limited area around the conductors. Small total length of the conductors on the other hand increases the current density in the soil around the conductors. Following the basic relation $E = \sigma J$, a higher current density leads to higher electric fields, which in turn results in a more pronounced soil ionisation. This is seen best when comparing the results of the 1 ring design without soil ionisation (max. step voltage U_S = 178 kV) against the result of the same design with soil ionisation (max. step voltage U_S = 56 kV).

Also remarkable is the fact that all step voltages, regardless of the individual design of the earth termination system, converge against a common distribution outside the direct influence of the earth termination system. For more compact designs, this is the case for about r > 15 m (see Figure 2), for more extended designs, the distributions converge at around r > 25 m. (see Figure 3).

Comparing the results, it is also clear that generally speaking, earth termination designs with a large area of contact between conductors and soil buried deeply in the ground lead to lower step voltages on the surface. A good example for this is the comparison of the 1 ring design (conductor only 0.5 m below the surface, max. step voltage U_S = 178 kV in linear case) and the 6 m rods with isolated upper half (conductor >5 m below the soil, max. step voltage U_S = 21 kV in linear case).

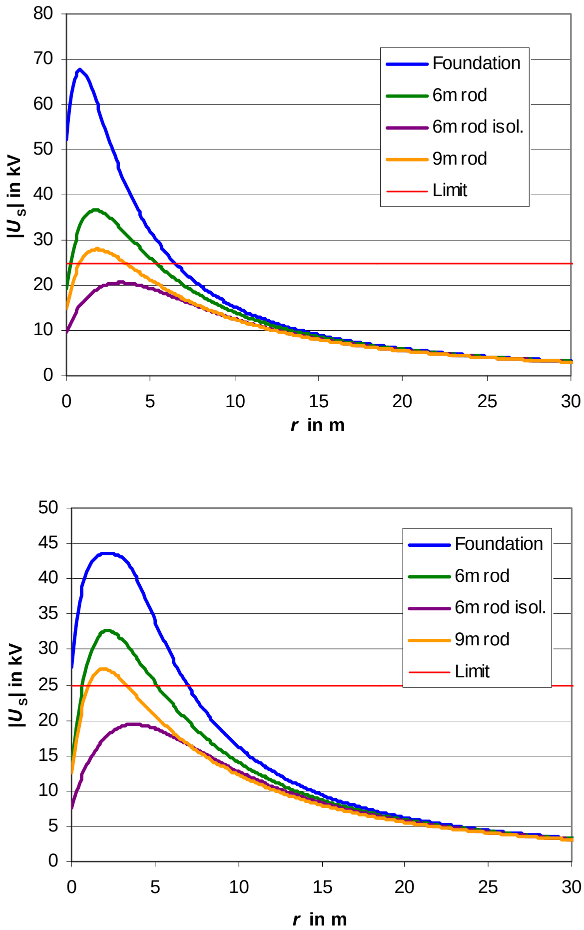

Figure 2: Step voltages of different earth termination system designs with linear soil (above) and non-linear soil (below).

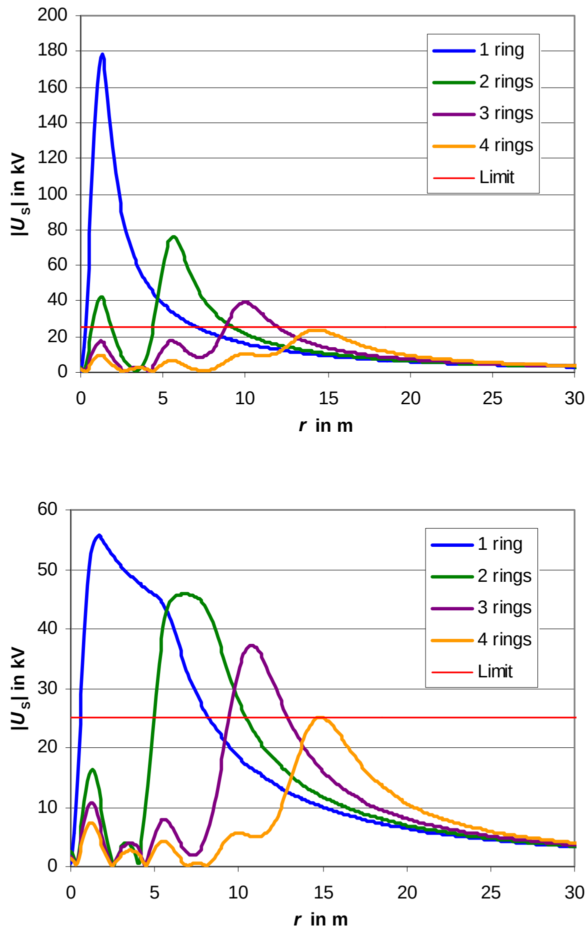

Figure 3: Step voltages of earth termination system designs with 1 to 4 rings, linear soil (above) and non-linear soil (below).

4 CONCLUSION

After an extensive literature research, a safety limit of step voltages for 10/350 µs impulses could be proposed. 3D FEM simulations of various earth termination designs have been successfully conducted, optionally also including the effect of soil ionisation. As preliminary conclusion, the consideration of soil ionisation leads to step voltages, which in some cases can be significantly lower than for linear soil. Also usage of very extended designs or designs deeply buried in the soil will result in lower step voltages.

The results from the aforementioned relations might lead to more economic, though even safer earth termination systems with regard to step voltages. More detailed investigations on this aspect will be performed in the further course of this project.

5 REFERENCES

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