Good Afternoon

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How grounds affect the peak voltage due to lightning

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In 1997 an experiment at the Camp Blanding center for lightning testing [1] challenged the view that ground rods are essentially resistive. What that experiment found was that lightning current waveshapes in a building grounding system and those entering the electrical circuits of the building were considerably different. That was at odds with IEC 61312-1:1995 [1] assertion that they should be the same, based on work done at power line frequencies. The conclusion of the Camp Blanding experiment was that for lightning, the ground rod had an impedance with a reactive component in addition to the resistive one.

So how do we take into account the impedance effects for lightning? Well it turns out not to be so simple. Professor Leonid Grcev, who with his students have conducted extensive studies of grounds, has found that a simple modeling of a ground rod as an R-L-C circuit doesn’t give correct results, due surge propagation effects, which cause a deviation from simple R-L-C behavior during the rise-time of the surge. So the challenge is to determine what this deviation is.

Considering normal grounds (those not chemically treated or otherwise enhanced), Grcev has shown that they can be characterized in terms of Effective Length l_{eff}, and Impulse Coefficient A [3]. The impulse coefficient is the ratio of peak voltage across an actual ground rod to the peak voltage across a purely resistive ground rod in response to a surge. It shows how the impedance of the ground rod affects the expected peak voltage due to a surge, relative to what it would have been if the ground rod were purely resistive.

The first thing to consider is the ground rod effective length, which is the length of the ground rod below which the ground rod is primarily resistive, with a possible capacitive effect, and above which the ground rod will have inductive effects. l_{eff} will be used later in the discussion of the Impulse Coefficient (which is needed to determine the peak voltage).

$$l_{eff} = \frac{1-\beta}{\alpha} \qquad (1)$$

Where

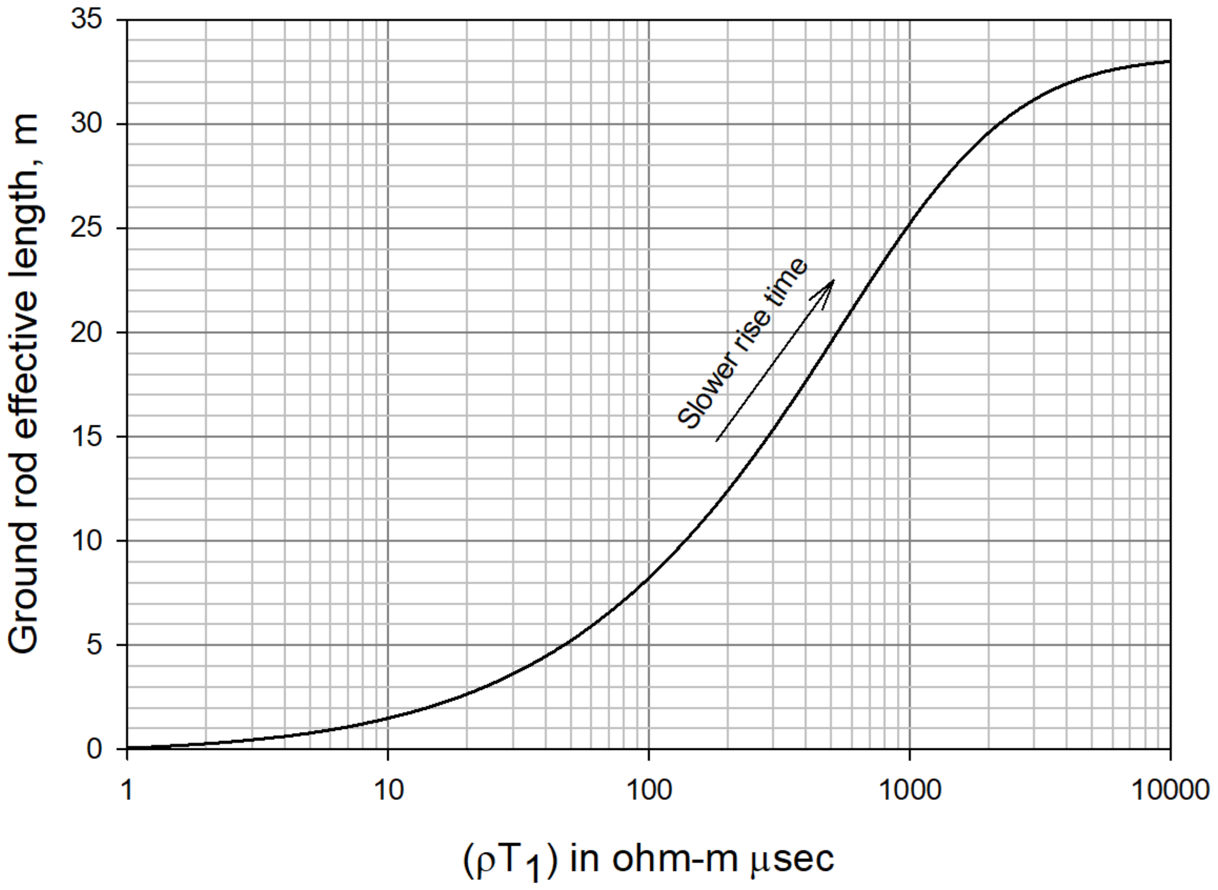
$$\alpha = 0.025 + exp[-0.82(\rho \cdot T_1)^{0.257}] \qquad (2)$$

$$\beta = 0.17 + exp[-0.22(\rho \cdot T_1)^{0.555}] \qquad (3)$$

ρ = soil resistivity in *ohm-m* (not the usual ohm-cm) and T_1 is the zero-to-peak rise time of the lightning current pulse.

MIL-HDBK419 Table 2.3 [6] shows a range for average soil resistivity of 100 to 50,000 ohm-cm (1 to 500 *ohm-m*). CIGRE TB549 Table 3.5 [7] shows a range of front durations T_1 of 1.1 µsec for the average subsequent stroke to 18 µsec for the maximum first stroke. Considering those values, the ρT_1 product could reasonably range from 1 to over 10,000 ohm-m-µsec.

We can use (2) and (3) to make a plot of I_{eff} vs. ρT_1, as shown in the next slide



This Figure shows the variation in the effective length of a ground rod with the product of soil resistivity and the zero-to-peak time of the surge.

As an example, for a ρT_1 product of 200, ground rods shorter than 13 m will have capacitive effects, and longer than 13 m will have inductive effects

Impulse Coefficient

In general, if the length s of the ground rod is less than l_{eff} the ground rod is primarily resistive, generally with a capacitive effect. If the length s of the ground rod is greater than l_{eff}, the ground rod will have inductive effects.

What is the consequence of the reactive effect? Well that's what the Impulse Coefficient A determines.

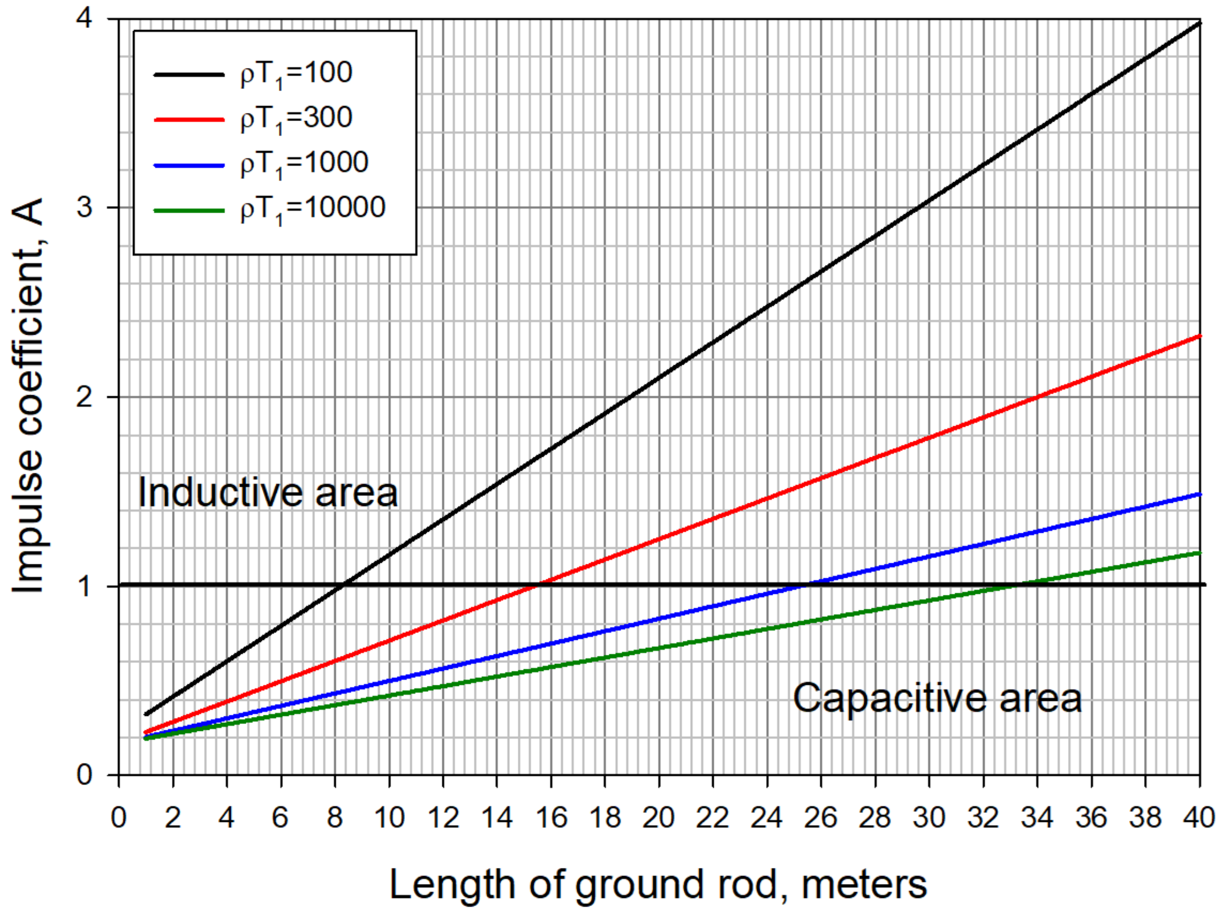
$$A = \alpha s + \beta \qquad (4)$$

where the impulse coefficient A = Z/R, R is the ground rod resistance, Z is the *effective* ground rod impedance, s is the length of the ground rod, α is calculated from equation (2) and β is calculated from equation (3).

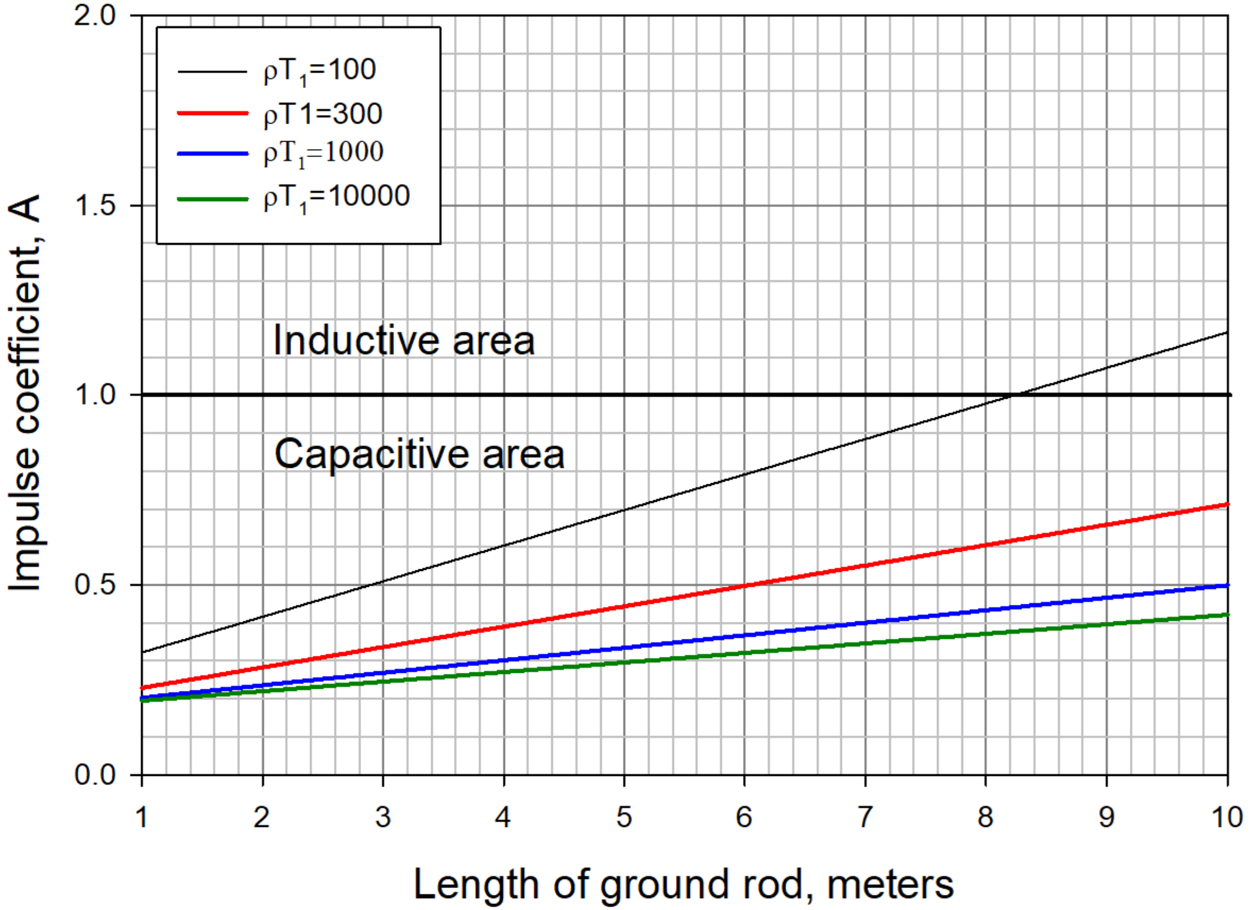
For A > 1, the ground rod has an effective series inductance in addition to its resistance. In this case the peak voltage will be A times bigger than it would have been if the ground rod were purely resistive.

For A < 1, the ground rod has an effective parallel capacitance in addition to its resistance. In this case the peak voltage will be A times lower than it would have been if the ground rod were purely resistive.

From (4) the effect of the ground rod reactance can be calculated. As an illustration, take the four cases of ρT_1, = 100, 300, 1000 and 10,000 and use (4) to plot A vs. length of rod. The result is shown in the next slide.



This plot shows that ground rods with a low ρT_1 product tend to look inductive, whereas ground rods with a high ρT_1 product tend to look capacitive.



This is a replot of the previous slide for ground rods of a length normally used (≤ 10 m).

Generally these ground rods will look capacitive during the rise-time of the surge.

For ground rods < 10 m the low value of the impulse coefficient means that the peak voltage across the ground rod will generally be less than would be calculated for a purely resistive ground rod. For example, for a 2 m rod the ratio of peak voltage to the peak voltage across a purely resistive ground rod is in the range 0.2 to 0.4, depending on the ρT_1 product.

Remember that the impulse coefficient is relevant only during the rise-time period. So during the surge decay, the voltage across the ground rod is determined primarily by the native impedance of the ground rod.

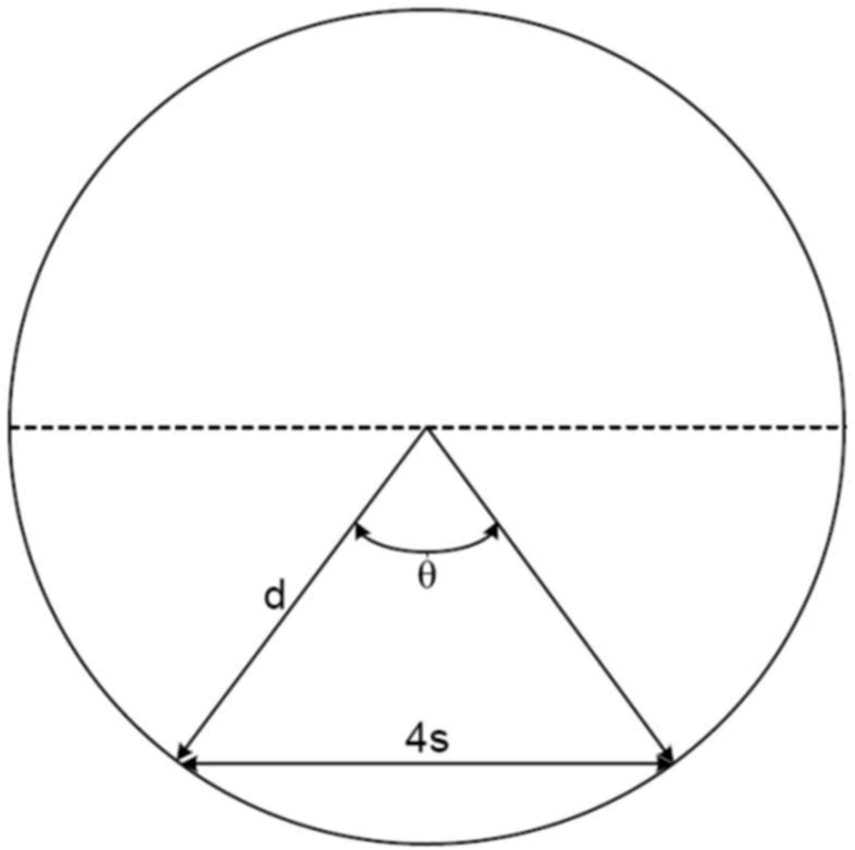
Peak voltage (the point of this whole discussion)

The peak voltage developed across the ground rod is given by

$$V_{peak} = ZI_{rod} \qquad (4)$$

Where I_{rod} is the peak current captured by the ground rod, and *Z* is the ground rod *effective* impedance.

To calculate the ground rod current we need to calculate the fraction of the lightning current I_{max} captured by the ground rod. IEEE Std 142 [5] shows that 99% of the current flowing in the ground rod is captured in a volume having a radius of twice a ground rod length s, as illustrated in the next slide.



The angle θ subtended by the ground rod is given by

$$\theta = 2\arcsin(2s/d) \qquad (6)$$

Where s is the length of the ground rod and d is the distance from the lightning strike point to the edge of the cylinder representing the ground rod outer effective extent.

Note that the arcsin is not defined for arguments greater than 1, so there are two cases for equation (6): Case 1 where d ranges from 2s to infinity, and case 2 where d ranges from 2s to 0.

For case 1, if the arcsin is in degrees, then the fraction f_1 of the lightning current I_{max} captured by the ground rod is

$$f_1 = \frac{2\arcsin\left(\frac{2s}{d}\right)}{180} = \frac{arcsin\left(\frac{2s}{d}\right)}{90} \qquad (7)$$

For case 2, the fraction f_2 of the lightning current Imax captured by the ground rod is

$$f_2 = \frac{arcsin\left(1-\frac{d}{2s}\right)}{90} \qquad (8)$$

So $I_{rod} = I_{max}(f_1 + f_2)$, which is

$$I_{rod} = I_{max}\left\{\left[\frac{arcsin\left(\frac{2s}{d}\right)}{90}\right] + \left[\frac{arcsin\left(1-\frac{d}{2s}\right)}{90}\right]\right\} \qquad (9)$$

Remember that in calculating I_{rod}, the first term in equation (9) is only valid for d greater than 2s, and the second term is only valid for d less than 2s.

The peak voltage is calculated from equation (5). The effective impedance Z of the ground rod to be used in equation (5) can be calculated from Dwight's [4] equation multiplied by A:

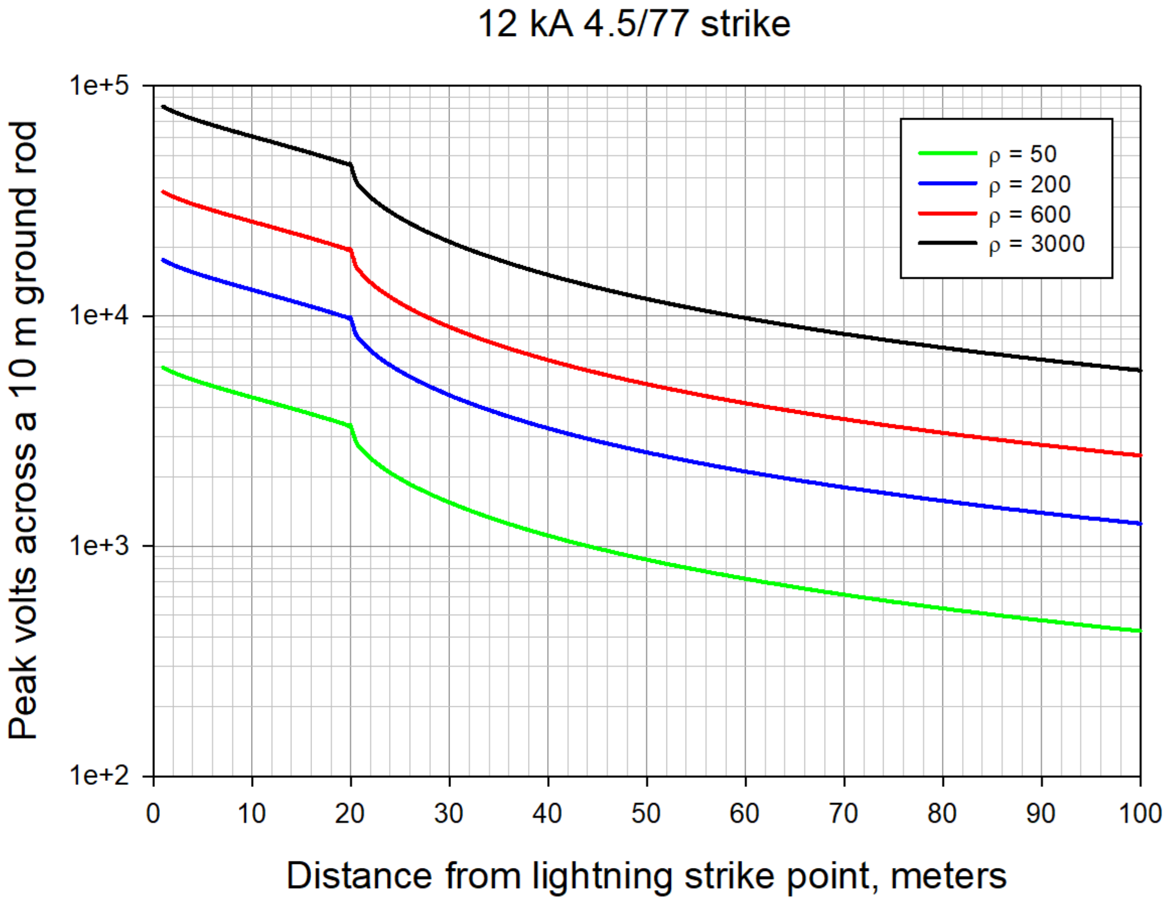
$$Z = \frac{A\rho}{2\pi s}\left[ln\left(\frac{4s}{a}\right) - 1\right] \qquad (10)$$

where *a* is the diameter of the ground rod

Substituting equations (9) and (10) in equation (5)

$$V_{peak} = \frac{A\rho I_{max}\left[arcsin\left(\frac{2s}{d}\right)+arcsin\left(1-\frac{d}{2s}\right)\right]}{180\pi s}\left[ln\left(\frac{4s}{a}\right) - 1\right] \qquad (11)$$

As an example of the calculation of the peak voltage, consider a 12 kA 4.5/77 subsequent surge from TB549 [7] impinging on a 10 m ground rod 2.5 cm in diameter in soils of 50 ohm-cm, 200 ohm-cm 600 ohm-cm and 3000 ohm-cm. For these cases, the next slide shows the peak voltage V_{peak} as a function of the distance from the lightning strike.



This graph shows how the peak voltage changes with distance from the lightning strike point.

The non-liner shape of the curves is due to a decrease in ground-rod current capture cross section as the distance d increases.

Different lightning waveforms, different ρ and different ground rod lengths will result in different peak voltages than those shown in the graph.

As a note, the grey streaks in this picture show a region where the ground is ionized due to the high electric field caused by a lightning strike. In this area ρ is highly variable and basically unknown, so calculations of peak voltage in this region are essentially invalid.

As an estimate, calculations are likely invalid in the first 6 m from a lightning strike.

Summary

The usual assumption that ground rods are purely resistive is actually not what is observed in the case of lightning. Particularly for the relatively short ground rods generally in service, during the rise-time period the ground rods look like a time-varying impedance with a significant capacitive component. The result is that for these commonly used ground rods the peak voltage due to a lightning strike is often significantly lower than would be the case for a purely resistive ground rod.

Whether the peak voltage is higher or lower than for a purely resistive ground rod depends on a number of variables, including the surge waveform, the ground resistivity, the length of the ground rod, and the distance the observer is from the lightning strike point. The peak voltage across the ground rod can be calculated, based on estimates of these variables.

References

[1] IEC Standard 61312-1, Protection Against Lightning Electromagnetic Impulse- Part 1: General Principles. General Principles.

[2] V. A. Rakov et al, “Direct Lightning Strikes to the Lightning Protective System of a Residential Building: Triggered-lightning Experiments,” IEEE Transactions on Power Delivery vol. 17, no. 2 (April 2002).

[3] L. Grcev, “Impulse Efficiency of Ground Rods,” IEEE Transactions on Power Delivery vol. 24, no. 1 (January 2009), 441-451.

[4] H. B. Dwight, “Calculation of Resistances to Ground,” Transactions of the American Institute of Electrical Engineers vol. 55 (1936), 1319-1328.

[5] MIL-HDBK419, military handbook grounding, bonding, and shielding for electronic equipments and facilities, volume 1 of 2 volumes on basic theory, January, 1982.

[6] Cigre TB549, Lightning Parameters for Engineering Applications, August 2013.

Questions?

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