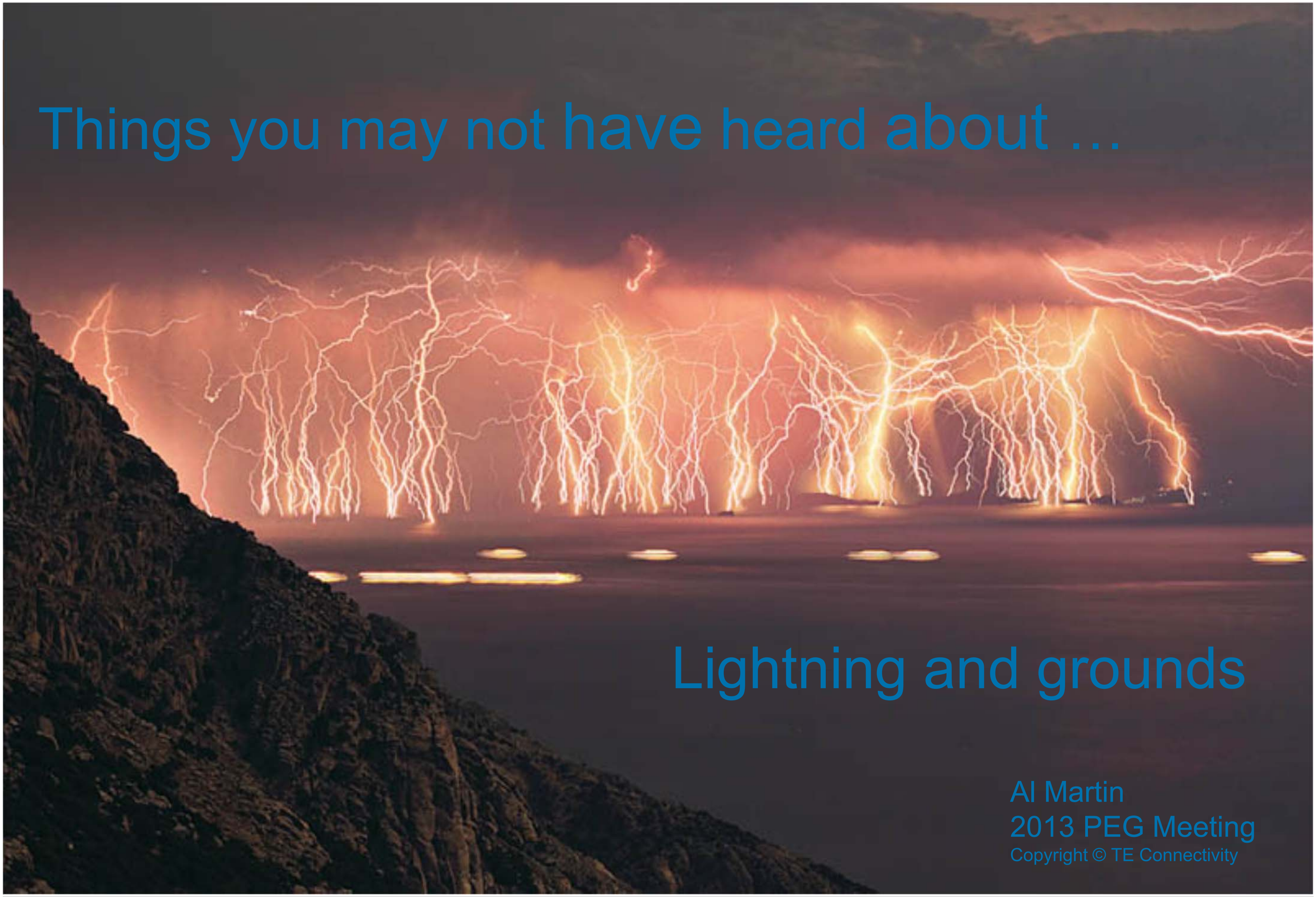
Things you may not have heard about …



Lightning and grounds

Al Martin
2013 PEG Meeting

A comment

The obvious solution to a problem isn't always the best:

A question

For example, would making a grounding rod longer or a grounding system bigger always reduce the risk of lightning damage?

TE
connectivity

Lightning measurements at structures

One way to set expectations is to study the effect of a ground rod on the waveshape of a surge, which can tell us a lot about how the ground rod is behaving.

Standards have advice on this. For example based on a reading of the IEC 61312-1 [4] standard, we might assume that the waveshapes of the current flowing in the grounding system and that flowing in the electrical circuit are the same – implying that the grounding system is simply a resistance.

But is that really the case?

Lightning measurements at structures

For another view, consider the work of Rakov, Uman and their associates at the Camp Blanding triggered lightning facility in Florida. They have a facility with a launch tower [for rocket-induced lightning] and an instrumented building. They have shown [2] that the waveshapes of the currents in the grounding system and those entering the building electrical circuits are considerably different [in their case for a subsequent surge]; and they attribute the difference to the performance of the ground rods in the two cases.

That observation suggests that we need to look more closely at the effects of ground rods on an incident lightning waveform. Maybe ground rods can act differently than the IEC expects.

Lightning measurements at structures

From the recorded the waveforms of the currents at the launch tower and at the ground rods, Rakov *et al* found that the surge *currents* in the ground rods have a much faster rise time and a much shorter duration than those of the incident surge....

Hmmm… so what's going on?

Lightning measurements at structures

The short explanation is that the ground rods used in the study by Rakov *et al* are acting like lossy capacitors* – probably not what most of us would expect.

Ground rods may have other behavior that we don't expect, so let's look at what is known about them.

*A steep rise-time is characteristic of the current flow in a parallel RC circuit

Ground rods [or horizontal ground wires]

The analysis of the behavior of ground rods also applies to horizontal ground wires, so in what follows the term “ground rods” will also include horizontal ground wires.

Generally ground rods are expected to behave like resistors. The unexpected behavior occurs because ground rods also have reactive elements.

Ground rods [or horizontal ground wires]

The effect of reactive elements on the waveshape of a surge will be greatest on high frequency components of the surge. The high frequency components of the surge affect primarily the surge rise-time, so the reactive elements of a ground rod may change the rise-time of the surge. The fall-time is generally less affected, depending on the type of surge and the resistance of the ground rod.

So let’s see how this happens…

Ground rods [or horizontal ground wires]

Quite a bit of work has been done recently on the high-frequency behavior of ground rods, to assess the impact on lightning [5]. The results can be divided into 2 categories: Short ground rods which look capacitive, and long ground rods which look inductive [6].

Short ground rods

Short ground rods are most likely to be found at residences. From the work of Rakov et all we expect that for this case capacitance will be the issue. Lee *et al* [7] suggest that the capacitance of a ground rod can be calculated from

$$C = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\frac{4l}{d}} \text{ F/m} \qquad (1)$$

Where ε_r = relative permeability [generally taken as 10], ε_0 = 8.854x10-11 F/m, l = length of rod and d = diameter of rod.

From (1) C = 1.0 nF for a 3 m long rod.

Short ground rods

Alipio et al [8] offer a formula for calculating the real and imaginary parts of the conductivity of the soil as a function of frequency. This combined with the formula for resistivity can yield capacitance [from the reactance] as

$$C = \frac{11.71 * l}{\ln\left[\frac{4l}{d} - 1\right] * f^{0.294}} \text{ nF/m} \qquad (2)$$

Where f is the frequency in MHz.

From (2) C = 6.0 nF for a 3 m long rod at 1 MHz, and 23 nF at 10 kHz. The higher capacity at low frequencies is probably due to the ionic nature of the soil.

Short ground rods

Rousseau *et al* [9] offer measurements at Fort Blanding of the impedance of the ground rods at 63 kHz and 1 MHz, which can be used to estimate the capacity of the ground rods. The capacity generally comes out to be about 3 – 6 nF for a 3 meter length of ground rod.

Considering these estimates, the capacity of a 3 m long ground rod is about 5 nF.

The ground rod capacity is in parallel with the resistance of the ground, so the effect of the capacity depends in the resistivity of the soil.

Short ground rods

Recall that the resistance of a ground rod as a function of soil resistivity and length can be calculated from [10]:

$$R = \frac{\rho}{2\pi \cdot l}\left[\ln\left(\frac{4l}{a}\right) - 1\right]$$ ohms/m, for l >> a (3)

Where ρ is the resistivity of the ground, l is the length of the ground rod, and a is its diameter. The values of l/a typically run from about 280 for 2 m ground rods to 2520 for 32 m ground rods. Using a linear approximation for l/a, (3) can be expressed as a function of length and resistivity only as:

$$R = \frac{\rho}{2\pi \cdot l}\left[\ln(513 + 300 \cdot l) - 1\right]$$ ohms-m (4)

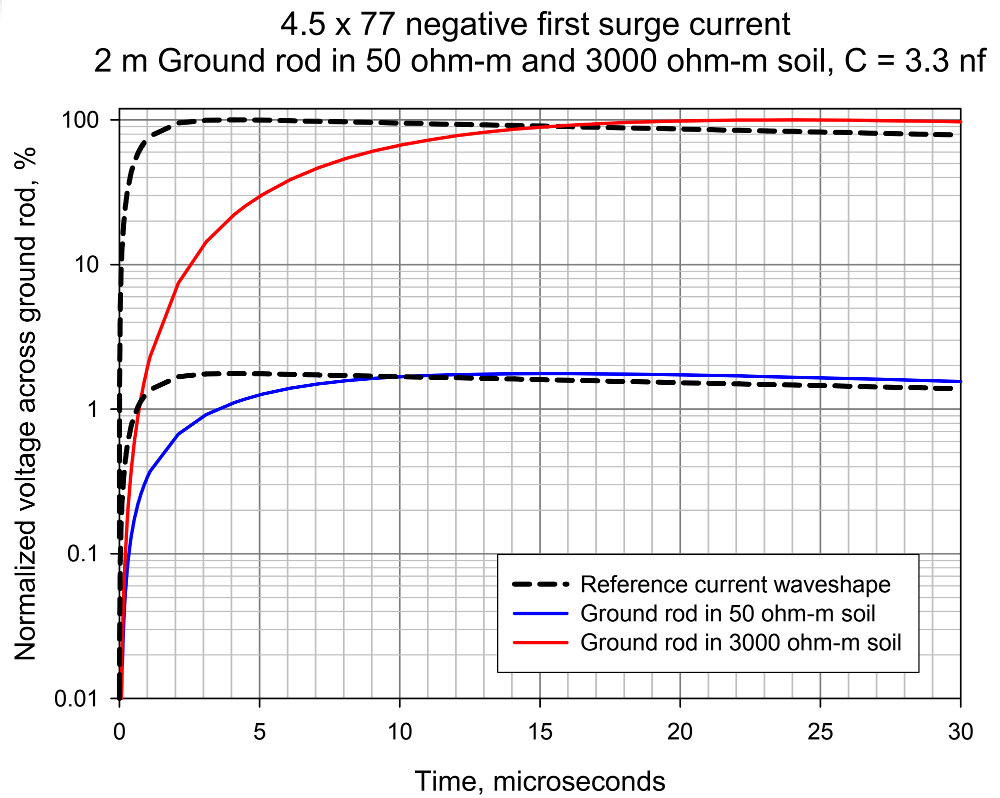
Equation (4) can be used to estimate the resistance of a ground rod as a function only of length and soil resistivity.

Short ground rods

The effect of ground rod capacitance can be shown by calculating the voltage waveforms developed across the ground rod by specified current waveforms and ground rod resistances.

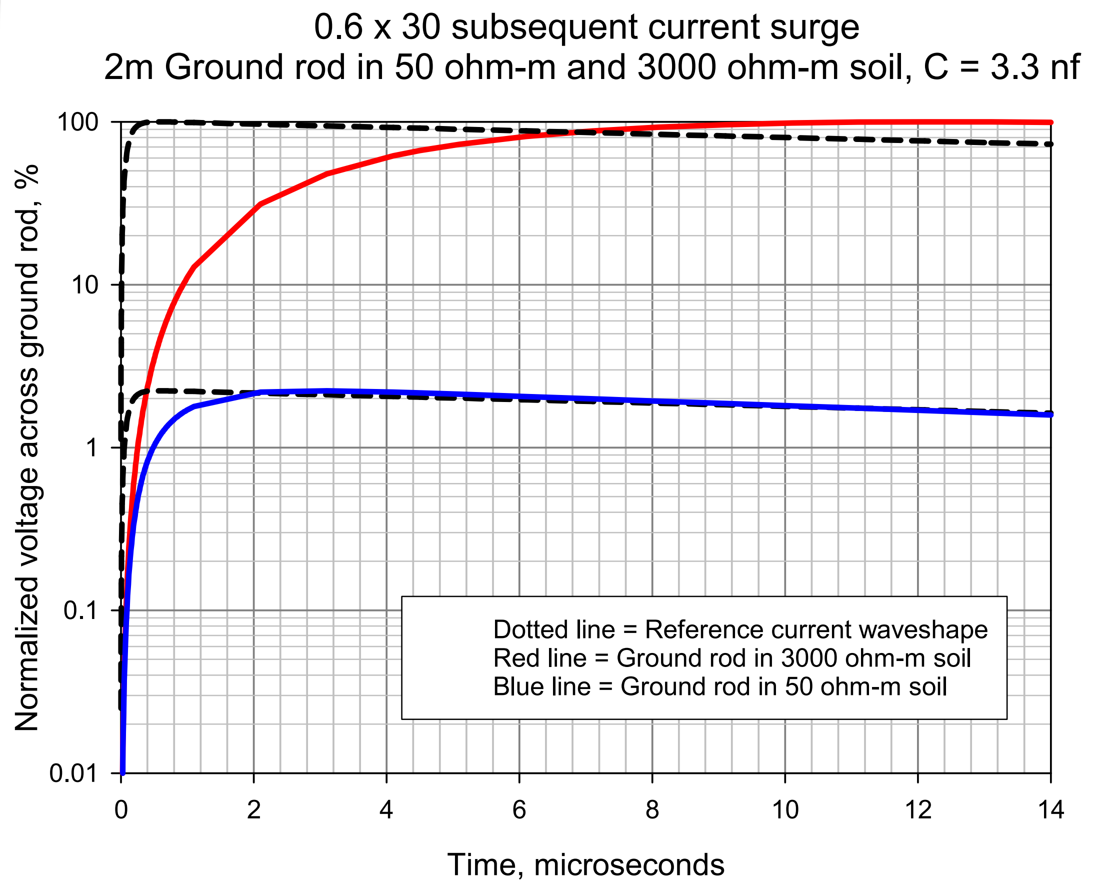
A typical short ground rod is 2 m long. From equation (4) this ground rod in low resistivity [50 ohm-m] and high resistivity [3000 ohm-m] soil would have a resistance of about 25 ohms and 1400 ohms, respectively. Using these resistances and assuming a capacitance of 3.3 nF (2/3 that estimated for a 3 m rod), the response to a first negative strike and a subsequent strike is shown in the next two slides.

Short ground rods



The effect of the ground rod capacitance is to slow the rise time of the voltage surge. The effect is greater in high resistivity [300 ohm-m] soil. The curve for the 3000 ohm-m soil is higher than for the 50 ohm-m soil due to the higher resistance of the ground rod, leading to a higher voltage for the same reference current.

Short ground rods



The effect of a short ground rod on a subsequent surge is similar to the effect on a first surge [the time scale is shorter due to the faster rise time of the subsequent surge].

Long ground rods

Long ground rods may be driven at commercial structures to lower the surge resistance to ground. Long horizontal ground wires and grounding grids also fall into this category. These have been characterized using transmission line analyses, e.g. Verma [11] for ground rods and wires; and Gupta [12] and Grecv [13] for grounding grids. Transmission line analysis is necessary for very long grounding systems [e.g. over 30 m], and may be appropriate for grounding systems down to 10 M in length.

For ground rods that are not too long [e.g. less than 30 m] it is simpler to calculate the inductance of the ground rod, and then calculate the response of a series R-L circuit.

Long ground rods

The inductance of the ground rod is given in Verma as:

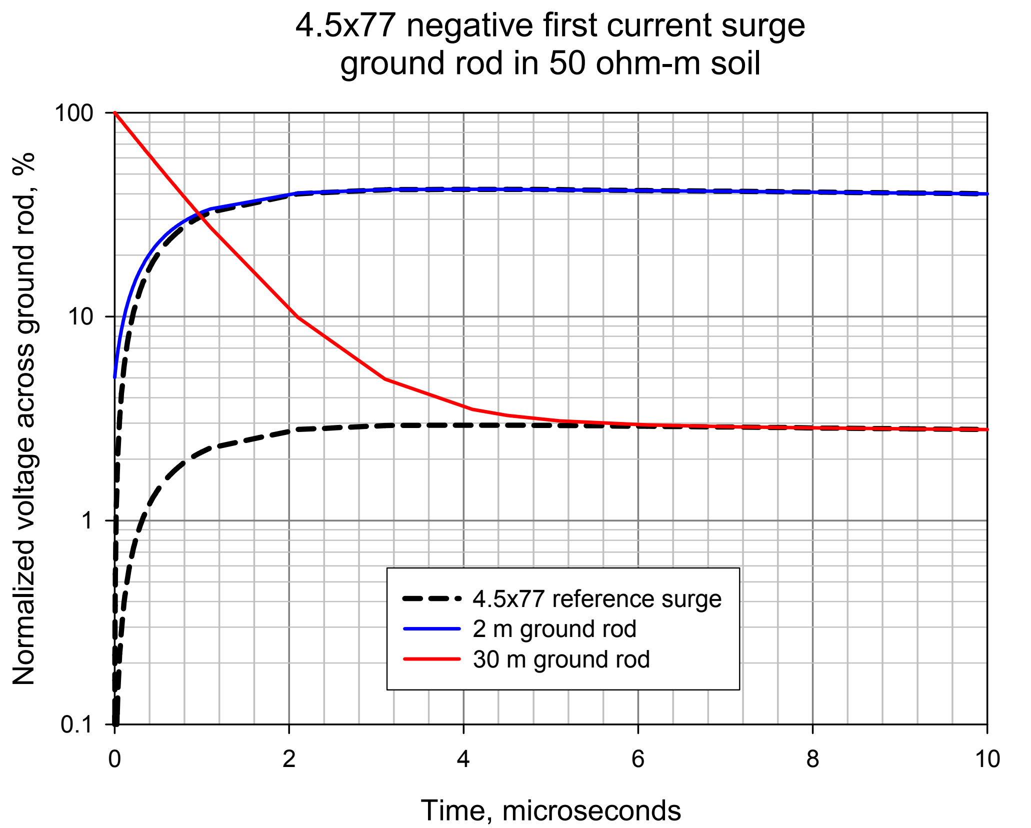
$$L = 0.2 \cdot \ln\left(\frac{2l}{a}\right) \ \mu\text{H/m} \qquad (5)$$

Where l and a are as given in (3). Using the same approximation as was used to obtain (4), (5) can be written as:

$$L = 0.2 \cdot \ln(256 + 150 \cdot l) \ \mu\text{H/m} \qquad (6)$$

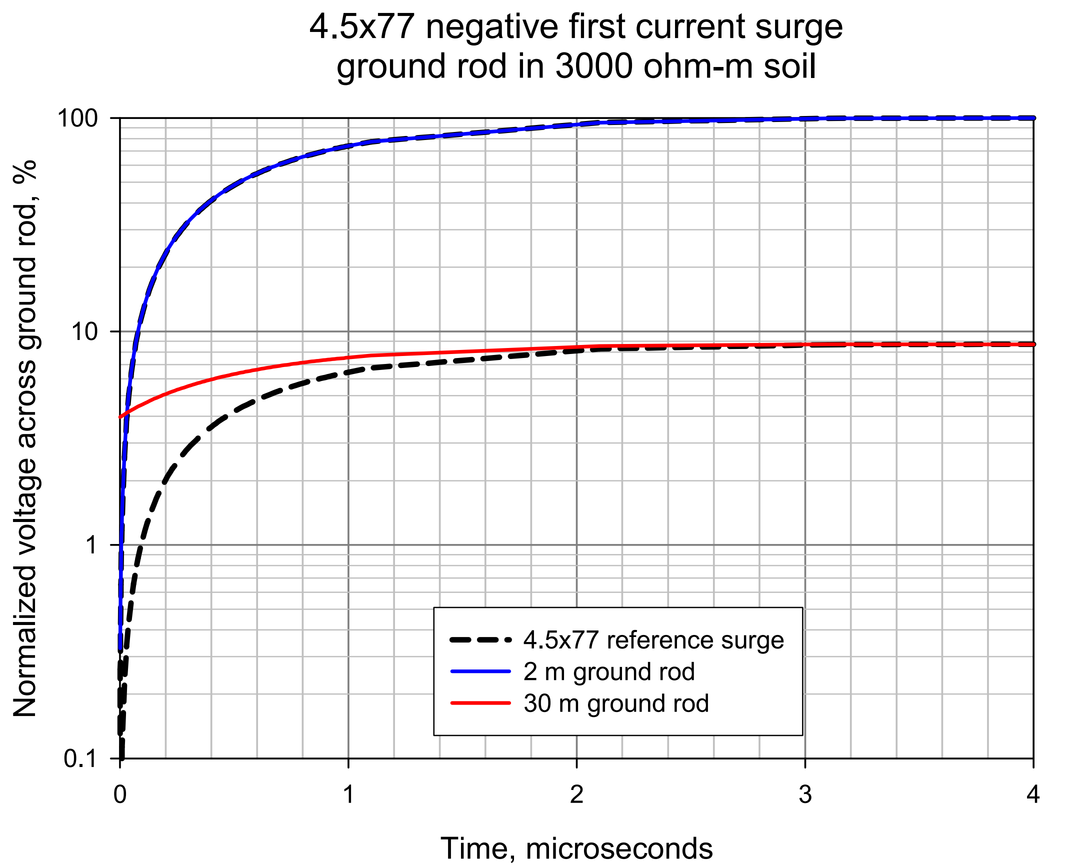
From (6) a 10 m ground rod has an inductance of 15 µH and a 30 m ground rod has an inductance of 51 µH.

Long ground rods



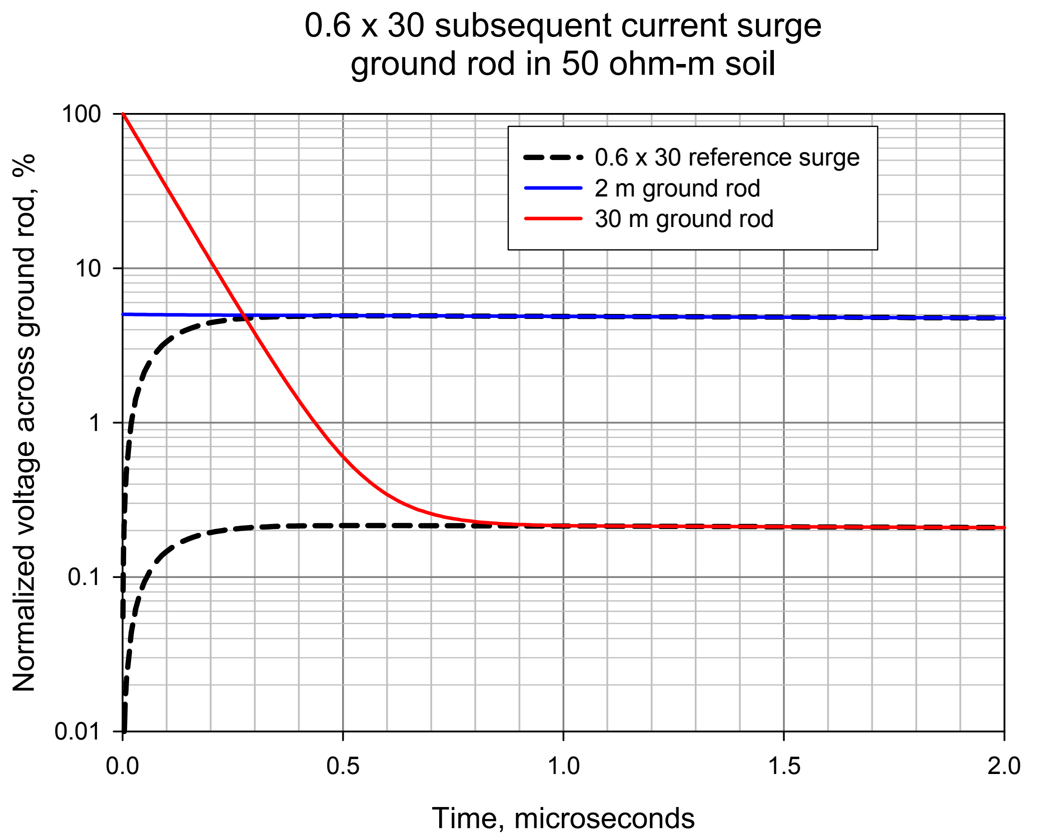
This figure shows that a short [2 m] ground rod has a small inductive effect on the negative first surge in 50 ohm-m soil, but a long [30 m] ground rod has a large inductive effect, causing a large voltage spike relative to a purely resistive ground rod. The 30 m rod has about 15x less resistance than the 2 m rod [hence lower ultimate voltage drop].

Long ground rods



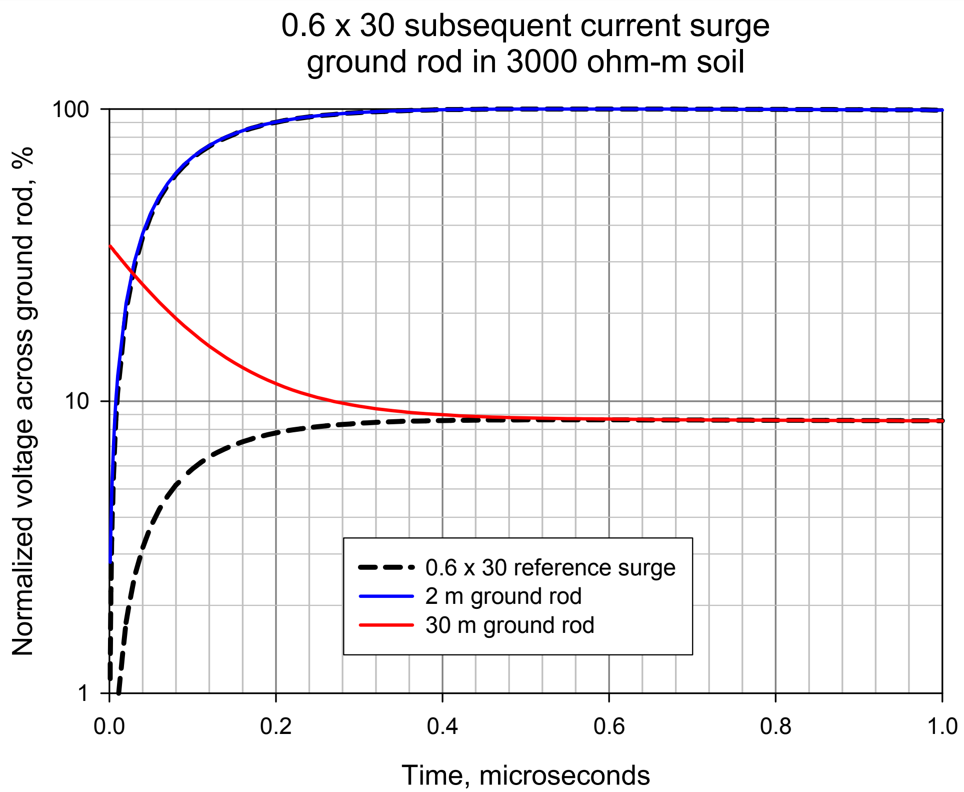
This figure shows that in high resistivity soil a short [2 m] ground rod has essentially no inductive effect on the negative first surge. A long [30 m] ground rod has a significant inductive effect relative to a purely resistive ground rod [but less than in 50 ohm-m soil].

Long ground rods



In low resistivity soil, a short ground rod has a relatively small inductive effect on a fast-rising subsequent surge [The initial shape of the curve in this case may be an artifact of the calculation]. A Longer ground rod [30 m] has a large inductive effect on a subsequent surge.

Long ground rods



This figure shows that in high resistivity soil a short [2 m] ground rod has basically no inductive effect on a subsequent surge, because its resistance dominates its inductance. A Longer [30 m] ground rod has a significant effect, but much less than it has in low resistivity soil.

Summary of short and long ground rods

The results illustrated above are dependent on the assumptions made in the calculations. Nevertheless some general conclusions can be drawn.

Short ground rods are most simply modeled by a parallel RC circuit, where the resistance is determined by the resistivity of the soil, and the capacitance can be estimated at about 3 nF. Long ground rods are most simply modeled by a series RL circuit, where again the resistance is determined by the resistivity of the soil. The table below summarizes general conclusions about the dominant effects of ground rod length and soil resistivity

Rod type and Soil resistivity	Reactive effect	Relative Resistance	Effect on rise time	Leading edge Spike	Voltage beyond the spike
Short, low ρ	Capacitive	Low	Least	None	Low
Short, high ρ	Capacitive	High	Most	None	High
Long, low ρ	Inductive	Low	Most	Highest	Low
Long, high ρ	Inductive	High	Least	Moderate	High

The practical effect of ground rods

We have seen how from a surge standpoint ground rods can be either capacitive or inductive in nature, depending on their length and the resistivity of the soil. The practical effect of a ground rod depends on the frequency content of the incident surge. A double exponential of the form

$$\exp(-at) - \exp(-bt)$$

Can be represented in the frequency domain as

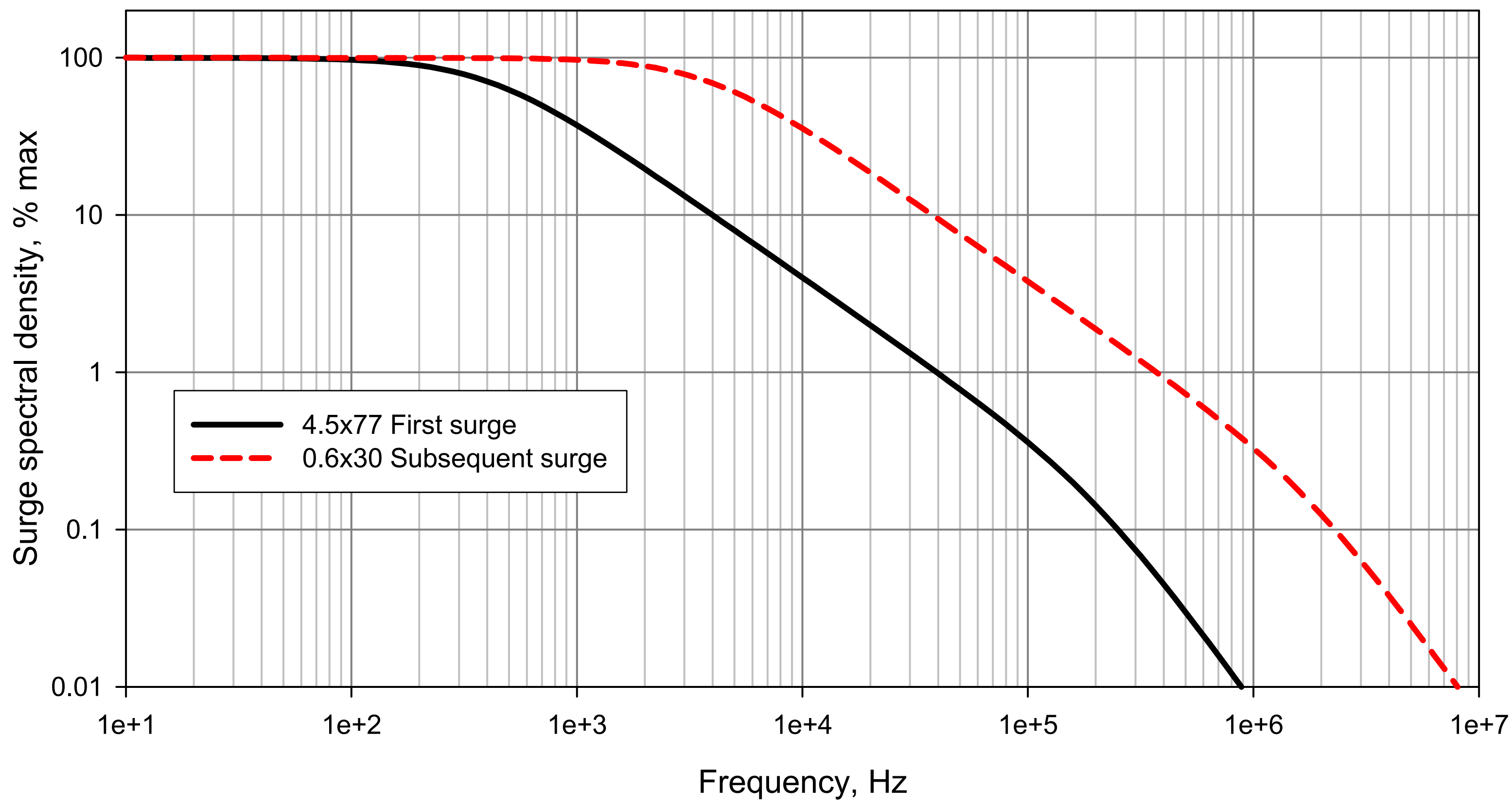
$$\frac{b-a}{(s-a)(s-b)} \qquad (7)$$

Where s = jω

The practical effect of ground rods

For the negative first surge we have been looking at, a = 2.52x10^3 and b = 1.26x10^6; and for the subsequent surge a = 2.38x10^4 and b = 1.11x10^7

So



The concept of Impulse Coefficient and Effective Length

What is clear from the previous slide is that the surge amplitude of both the 4.5x77 and the 0.6x30 surges is concentrated at low frequencies. At low frequencies a ground rod is essentially resistive. Since resistance decreases with the length of a ground rod, a long ground rod helps to reduce the specific energy [I^2t] of the surge by diverting the relatively high amplitude low-frequency components to ground. But a long ground rod looks inductive at higher frequencies, and this effect can lead to potentially damaging voltage spikes.

So at what length does the inductive effect become important?

The concept of Impulse Coefficient and Effective Length

Grecv [5] has defined the effective length of a ground rod as

$$l_{eff} = \frac{1-\beta}{\alpha} \qquad (8)$$

where

$$\alpha = 0.025 + \exp\left[-0.82(\rho \cdot T_1)^{0.257}\right] \qquad (9)$$

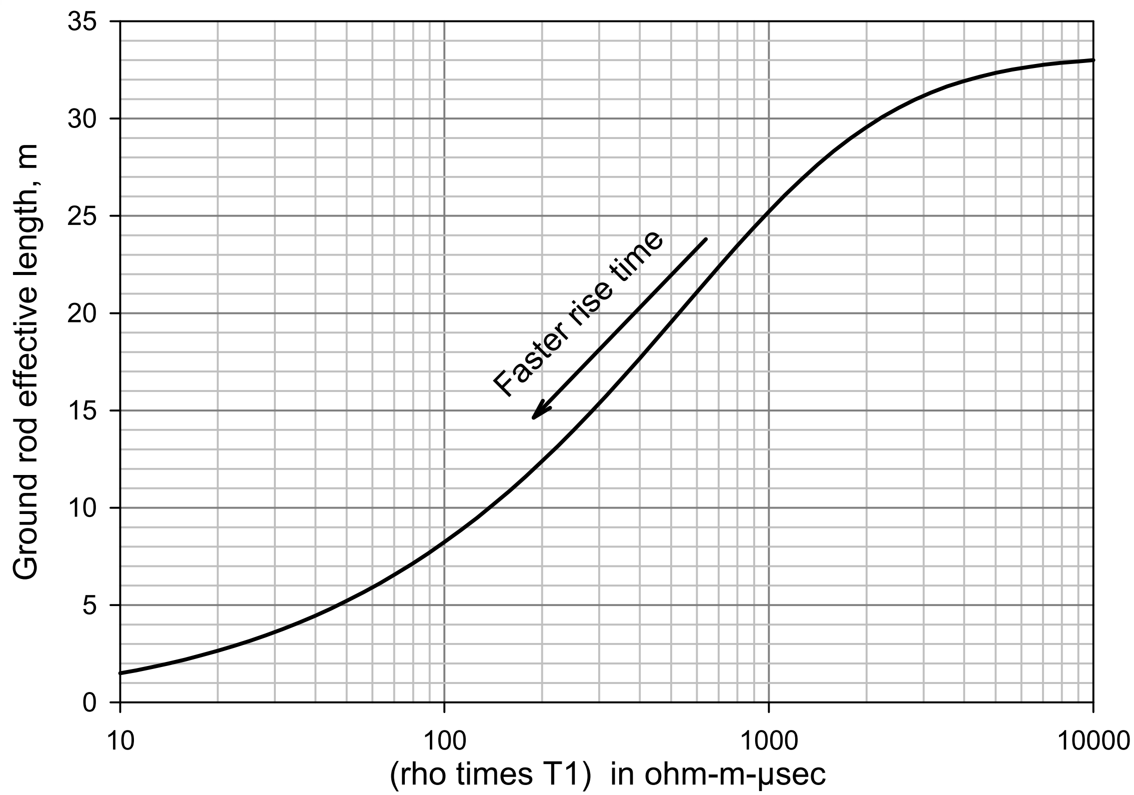
$$\beta = 0.17 + \exp\left[-0.22(\rho \cdot T_1)^{0.555}\right] \qquad (10)$$

ρ = soil resistivity in ohm-m

T_1 is the zero to peak rise time [in μsec] of the lightning current pulse.

We can use (8), (9) and (10) to make a plot of l_{eff} vs. ρT_1, as shown in the next slide.

The concept of Impulse Coefficient and Effective Length



This figure shows the variation in the effective length of a ground rod with soil resistivity and the zero to peak time of the surge, calculated using (8), (9), and (10).

The concept of Impulse Coefficient and Effective Length

If the length l of the ground rod is less than $leff$, the ground rod is primarily resistive, with a possible capacitive effect. If the length l of the ground rod is greater than $leff$, the ground rod will have inductive effects. As they are potentially damaging, how big are the reactive effects for a ground rod of a given length? Grecv [5] has proposed the relation

$$A = \alpha \cdot l + \beta \qquad (10)$$

Where A = Z/R is the impulse coefficient, and R = ground rod resistance

If A > 1, then the ground rod has a 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 [A gets bigger as the inductance increases].

If A < 1, then the ground rod has a 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 [A gets smaller as the capacitance increases].

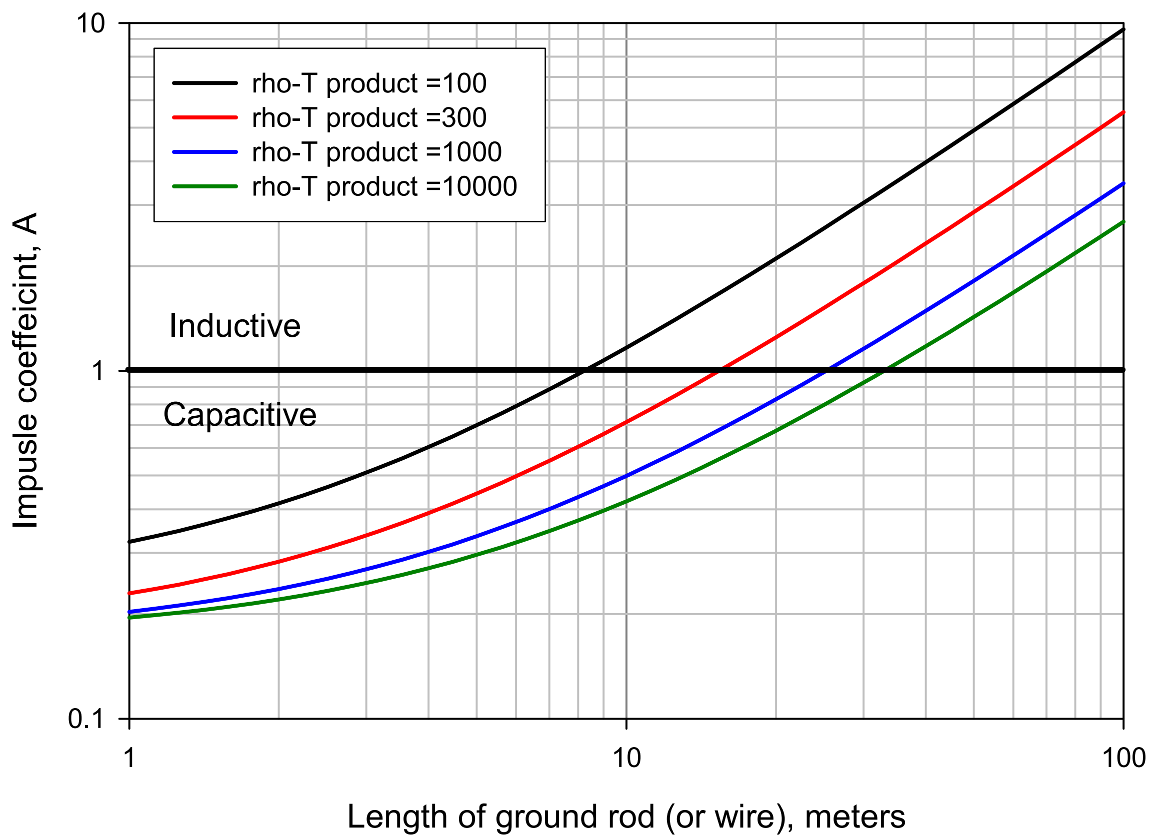
Using relation (10),

$$A = \alpha \cdot l + \beta$$

the effect of the ground rod reactance can be calculated.

As an illustration, take 3 cases of ρT_1, = 100, 300, 1000 and 10,000 and use (10) to plot A vs. length of rod [where T_1 is in microseconds]. The result is shown in the next slide…

The concept of Impulse Coefficient and Effective Length



This figure shows the impulse coefficient (the ratio of peak voltage to the peak voltage across a purely resistive ground rod or wire) versus length of ground rod (or wire).

Conclusion

Back in the beginning we said that the work of Rakov et al [7] was at odds with the IEC 61312-1 statement that the waveshapes of the current flowing in the grounding system and that flowing in the electrical circuit are the same. Now we can see that in order for the IEC 61312-1 statement about waveshapes to be valid, it must also assume that ground rods are purely resistive. Here we have shown that ground rods are resistive only under some conditions [more likely to be true for a first surge than a subsequent surge]; and that in general they also have a reactive component which can significantly affect the waveshape of the surge voltage [principally the leading edge], especially for subsequent surges.

So what's the point of all this?

The point is that when we think of grounding systems, we tend to think only of resistance, and how resistance can be reduced. But the things we do to lower resistance may increase inductance, which could actually make matters worse, especially for fast-rising secondary surges. This is something to bear in mind when designing protection, or creating new standards.

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And finally……

Questions?

or

Hakuna matata