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RELIABILITY AND SUSTAINABILITY

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Estimated Effects of Nearby Lightning: Too High or Too Low?

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Supposing we are considering the design of protection for a piece of equipment or a system. Generally direct strikes would be the main concern. However nearby strikes causing voltages and currents due to induction or induction combined with GPR are much more common, and stress the equipment differently. So we might want to consider whether these are significant, and a calculation might help decide if that could be the case.

In the case of induction, experience shows that calculations using the formulas presented in the literature generally give values that are too high.

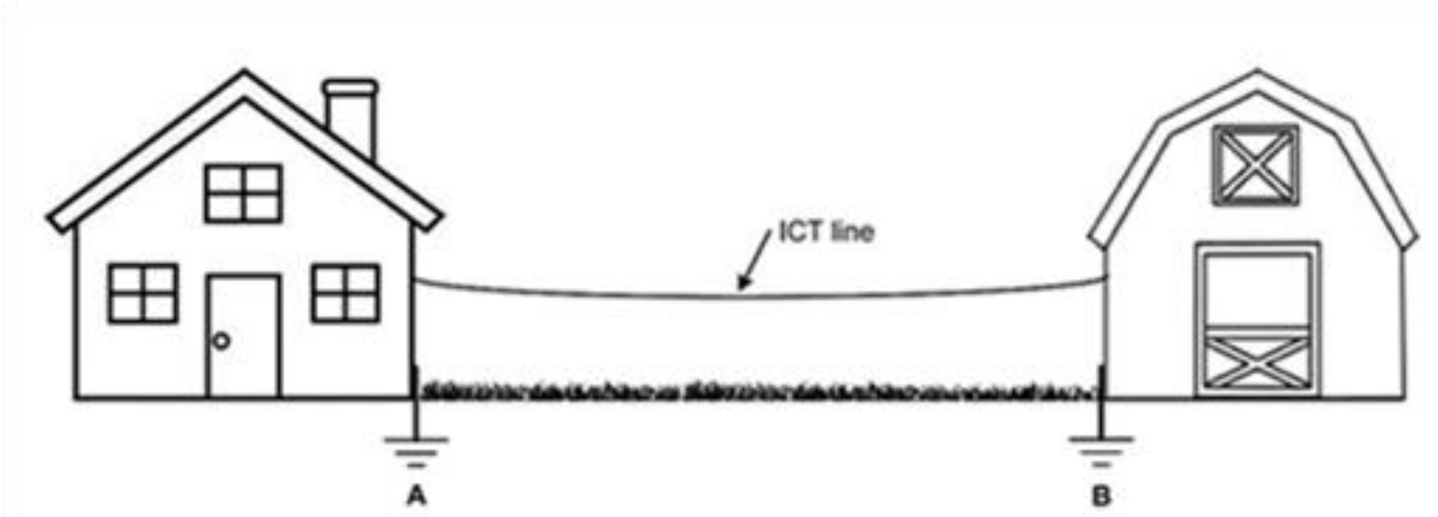
Conversely when GPR is combined with induction the values may be too low.

So why might these estimates be wrong? And if they are, can we get a better estimate?

With that in mind the plan is to show

- Why the effects of nearby lightning might be over-estimated, or in some cases under-estimated
- Show how to get more realistic estimates.

To get started, let's look at an application like the one shown below, which shows an ICT line running between two structures. The structures could possibly have grounds at A and at B

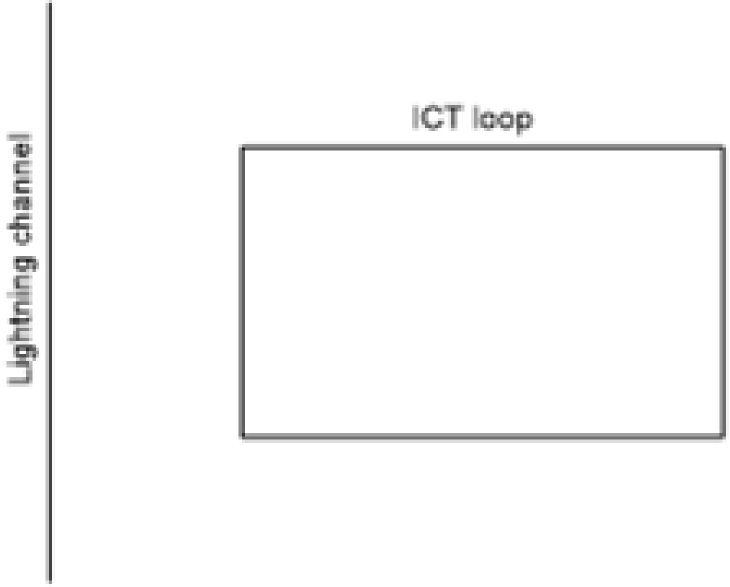


Consider induction alone

Let's begin by considering induction alone. For induction there are two cases to consider:

- If the common-mode impedance is high, then induced voltage can be high enough to cause insulation breakdown.
- If the common-mode impedance is relatively low (for example due to the operation of a surge protection device), the resulting current can potentially cause damage due to excessive I^2t.

Inductive effects are a result of the mutual inductance coupling between the lightning channel and the ICT circuit, so we need to begin by considering how that works. So this is what we have: A lightning channel modelled as a long straight wire and a nearby ICT loop



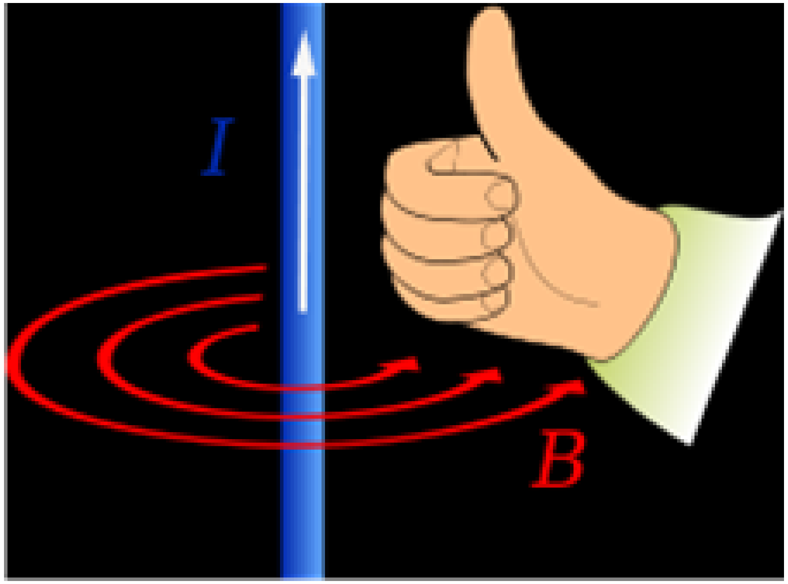
The mutual inductance *M* we need is given by:

$$M = \frac{\Phi}{I} \qquad (1)$$

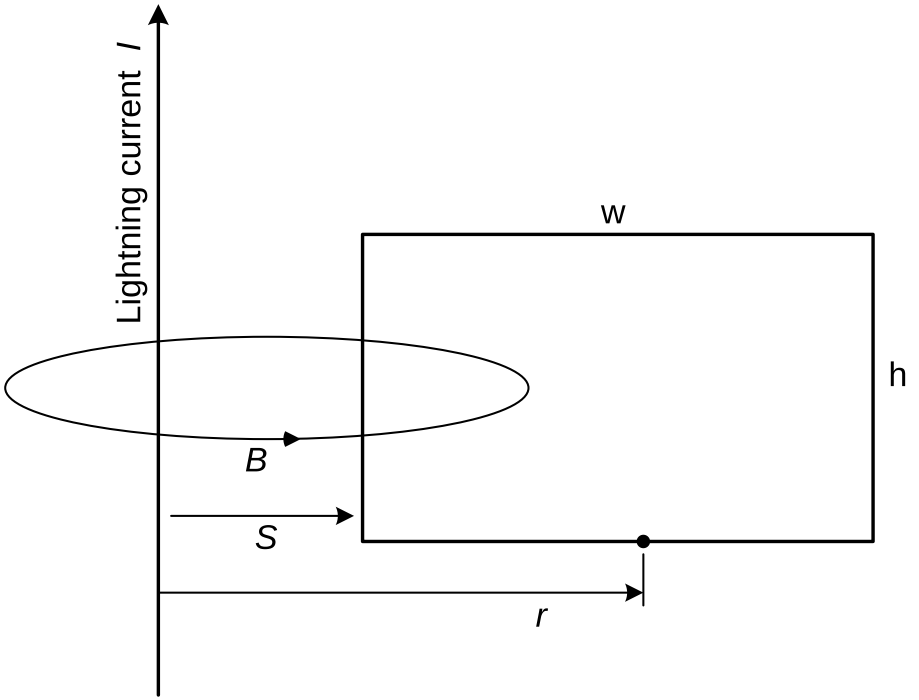
Where *Φ* is the *total* magnetic flux linking the loop, and *I* is the lightning current.

To find *M* in equation (1) we need to find *Φ*, which in turn is derived from the magnetic field B. So the first task is to get an expression for B.

By the right-hand rule, a current I causes a magnetic field B, which encircles the current channel like this:



So from the previous figure with the B-field added, the B field passes through the ICT loop like this:



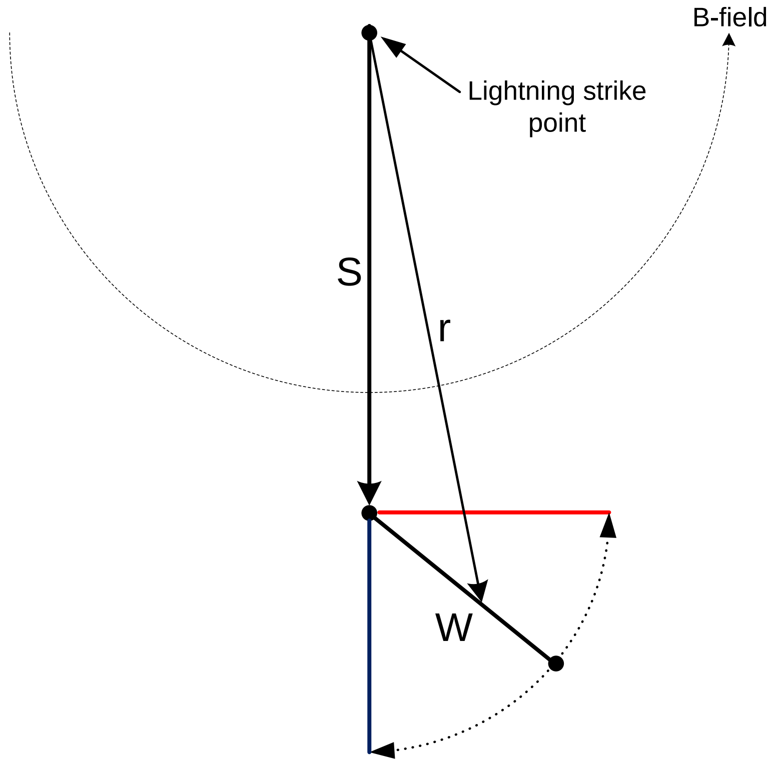
Here the lightning strike is a distance *S* from the nearest end of the ICT circuit, and a distance *r* from a point on the ICT loop. The ICT loop has a height *h* and width *W*.

Assuming that the ICT loop is unshielded and that the magnetic field is not distorted by the presence of other objects in the vicinity (basically we're talking about an open field), then B is given by

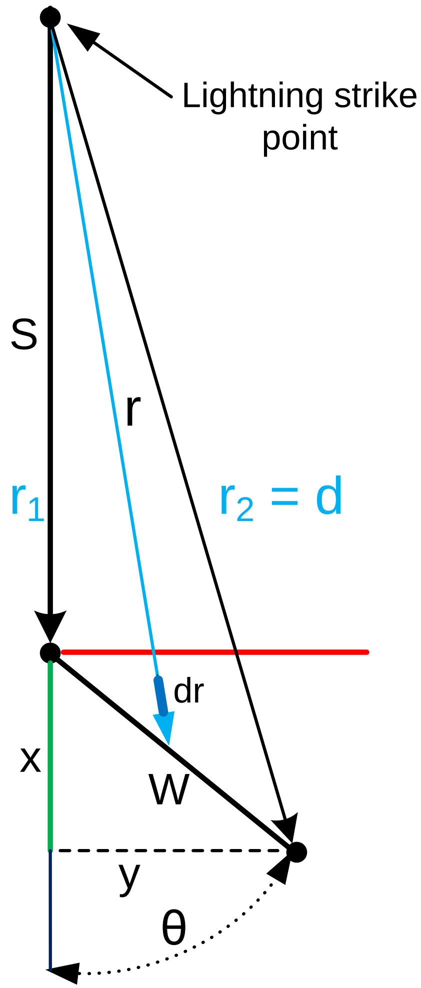
$$B = \frac{\mu_0 I}{2\pi r} \text{ webers/m}^2 \qquad (2)$$

Now to work on equation (2) we need to look at some geometry…

If the previous figure is rotated 90º to give a top view, then the Figure below shows that the ICT loop (labeled W) can take up any orientation from perpendicular to S (the red line) to parallel to S (the blue line).



Now remember that from equation (1), to find *M* we need to know the TOTAL FLUX Φ flowing through the loop area, which we get by integrating the B field over the loop area. So how do we do that?



An elemental loop area is dA = h(dr), where *h* is the loop height *dr* is a line element along the loop. Then using equation (2) for B

$$\Phi = \int_{r_1}^{r_2} B\,dA = \frac{\mu_0 I \mathrm{h}}{2\pi} \int_{S}^{d} \frac{dr}{r} \qquad (3)$$

where *r* is the distance from the lightning current channel to *dr*.

Now *d* is unknown, so we need to express it in terms of things we know (S, W and Θ). From the figure at left, where x = *WcosΘ* and y = *WsinΘ*

$$d = [(S + W\cos\theta)^2 + (W\sin\vartheta)^2]^{0.5}$$

Remembering that the limits of integration in equation (3) run from the beginning of the loop located at S to the end of the loop located at *d*, then doing the integration in equation (3):

$$\Phi = \frac{\mu_0 I h [ln(r)]_S^d}{2\pi}$$

And putting in the limits

$$\Phi = \frac{\mu_0 I \mathrm{h}\left[ln\frac{d}{S}\right]}{2\pi} \qquad (4)$$

We have a general expression for *d* (last slide), but there are two special cases of interest…

Consider the case where *Φ* is maximized, which occurs when θ = 0°. In that case d = S+W. Substituting this value for *d* into equation (4) and the result into equation (1)

$$M = \frac{\mu_0 \mathrm{h}\left[ln\frac{S+W}{S}\right]}{2\pi} \qquad (5a)$$

which is the same as usually given in calculations of induction due to lightning (e.g. ITU-T k.67 [1])

Substituting for $\mu_0 = 4\pi \times 10^{-7}$ H/m and re-arranging, the maximum value of *M* is

$$M = 0.2h\left[ln\left(1+\frac{W}{S}\right)\right] \ \mu\text{H} \quad (\theta = 0^{\circ}) \qquad (5b)$$

Now consider the case where Φ is minimized, which occurs when θ = 90°. In that case $d = S\left[1 + \left(\frac{W}{S}\right)^2\right]^{0.5}$ so

$$M = \frac{\mu_0 h}{2\pi} ln\left[1 + \left(\frac{W}{S}\right)^2\right]^{0.5} \qquad (6a)$$

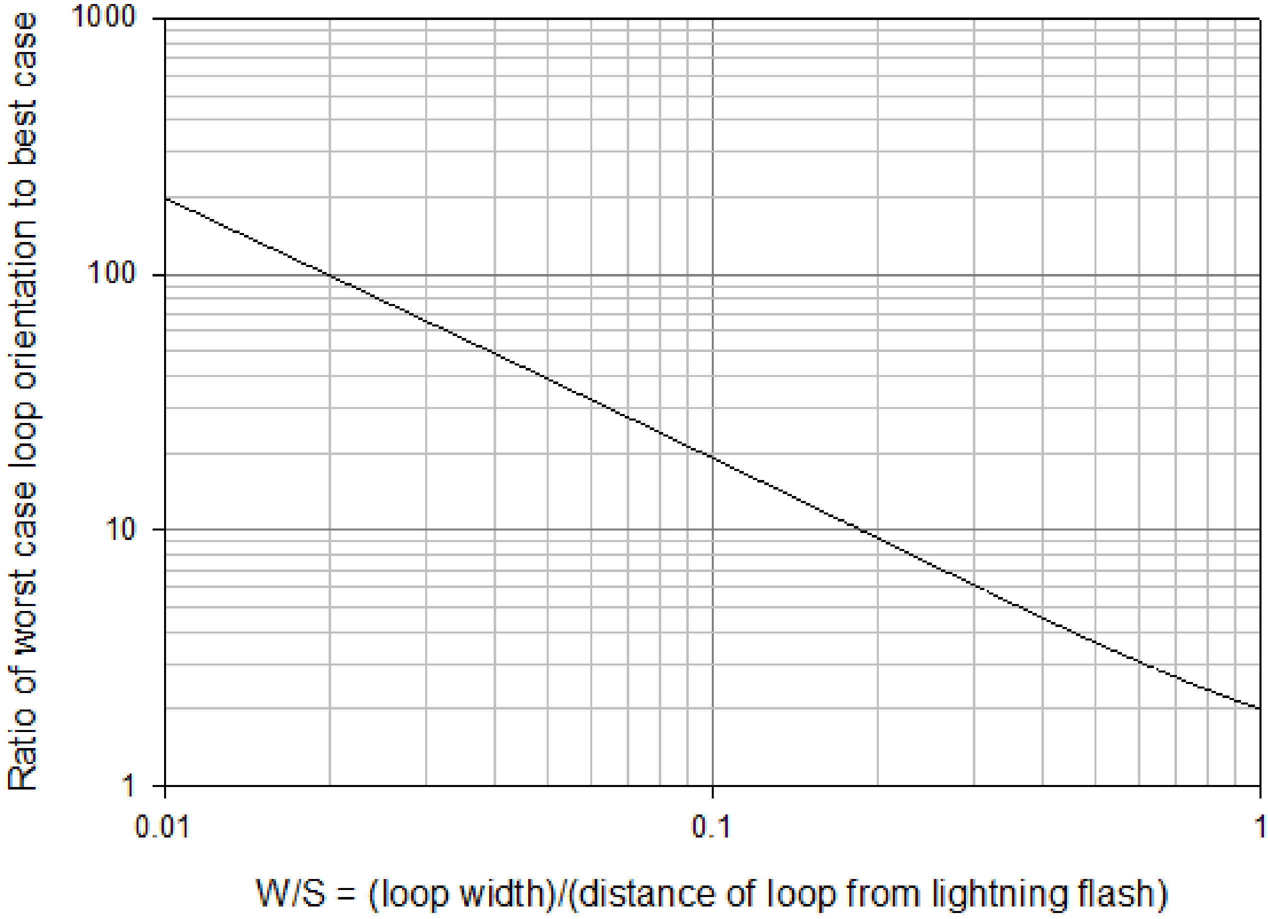
Substituting for $\mu_0 = 4\pi \times 10^{-7}$ H/m and re-arranging, the minimum value of *M* is

$$M = 0.2h\left\{ln\left[1 + \left(\frac{W}{S}\right)^2\right]^{0.5}\right\} \mu\text{H} \quad (\Theta = 90^\circ) \qquad (6b)$$

In general any loop orientation between the best case (θ = 90°) and the worst case (θ = 0°) is possible, so the value for M lies between that calculated from equation (5b) and that from equation (6b). For the general case of Θ, use

$d = [(S + W cos\theta)^2 + (W sin\vartheta)^2]^{0.5}$ in the calculation of M

A plot of the ratio of the worst case for M to the best case for M versus W/S is shown on the next slide. It's basically an estimate of the amount that M (and hence the induced voltage) could be over-estimated. It shows that loop orientation makes a big difference in the mutual inductance.



From this plot, over-estimates of M by a factor of 10 or more are possible.

Voltage calculations

Induced common-mode voltage: Calculation of V_{oc}

What we're really interested in is the open-circuit voltage V_{oc}, that occurs when the impedance is high, since this voltage is a potential cause of damage.

The induced common-mode voltage V_{2oc} due to a current i_1 in the lightning channel is just M times di/dt:

$$V_{2oc} = M \frac{di_1}{dt} \tag{7}$$

So from equation (5b) the maximum value of V_{2oc} is:

$$V_{2oc(max)} = 200h\frac{di}{dt}\left[ln\left(1+\frac{W}{S}\right)\right] \text{ V} \quad (\Theta = 0^o) \qquad (8a)$$

From equation (6b) the minimum value of V_{2oc} is:

$$V_{2oc(min)} = 200h\frac{di}{dt}\left\{ln\left[1+\left(\frac{W}{S}\right)^2\right]^{0.5}\right\} \text{ V} \quad (\Theta = 90^o) \qquad (8b)$$

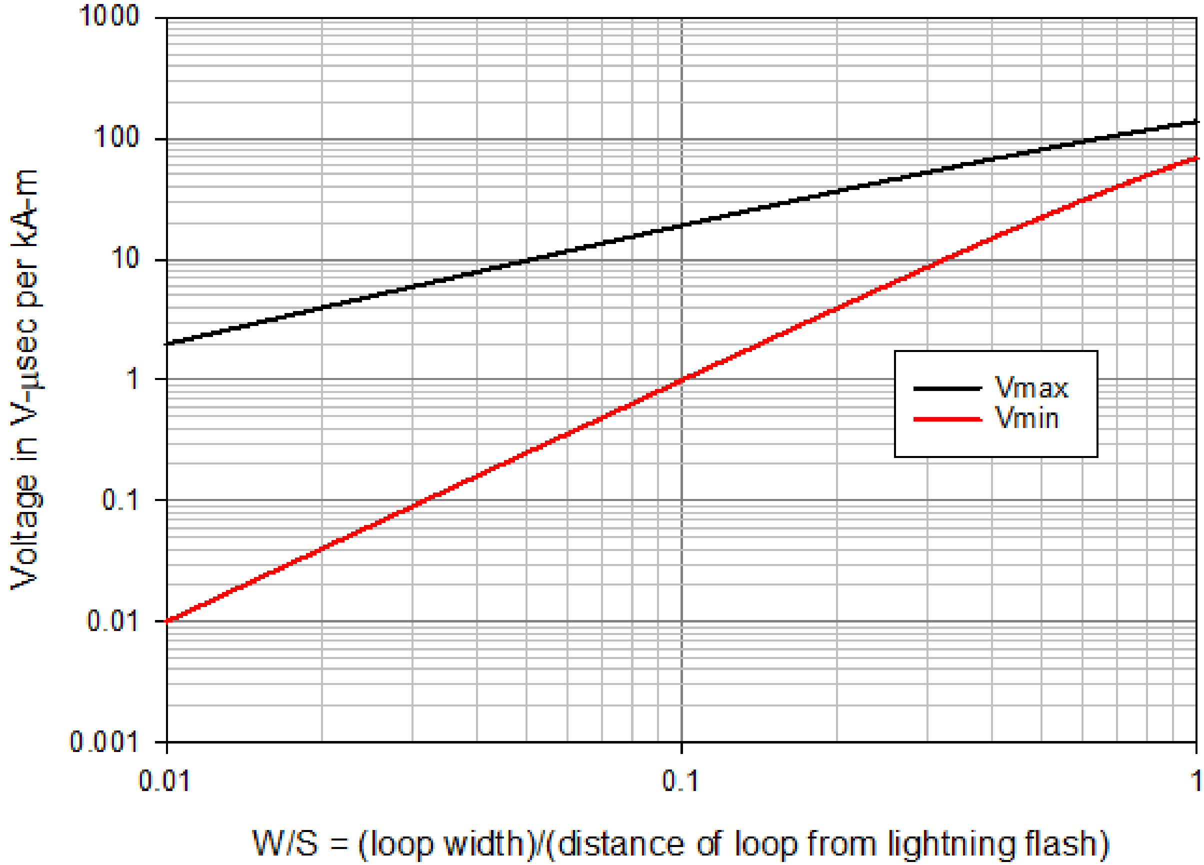
Where di/dt is in units of kA/µs.

As a sanity check we would like to know if the equations on the previous slide give a reasonable answer. Well there is an experimental result in ITU-T K.67 annex I.3 for the case where $\Theta = 0^o$, which allows us to check on equation (8a). In that experiment S = 100 m, W = 1.5 m, h = 2 m, di/dt = 26 kA/µs. Using these numbers in equation (8a) V_{2oc} = 116 V, which agrees very well with the 110 V measured in the K.67 recommendation.

So equation (8a) looks to be OK. We don't have a similar check for equation (8b), but it was derived using the same process as was used for equation (8a), so we'll assume it is OK also.

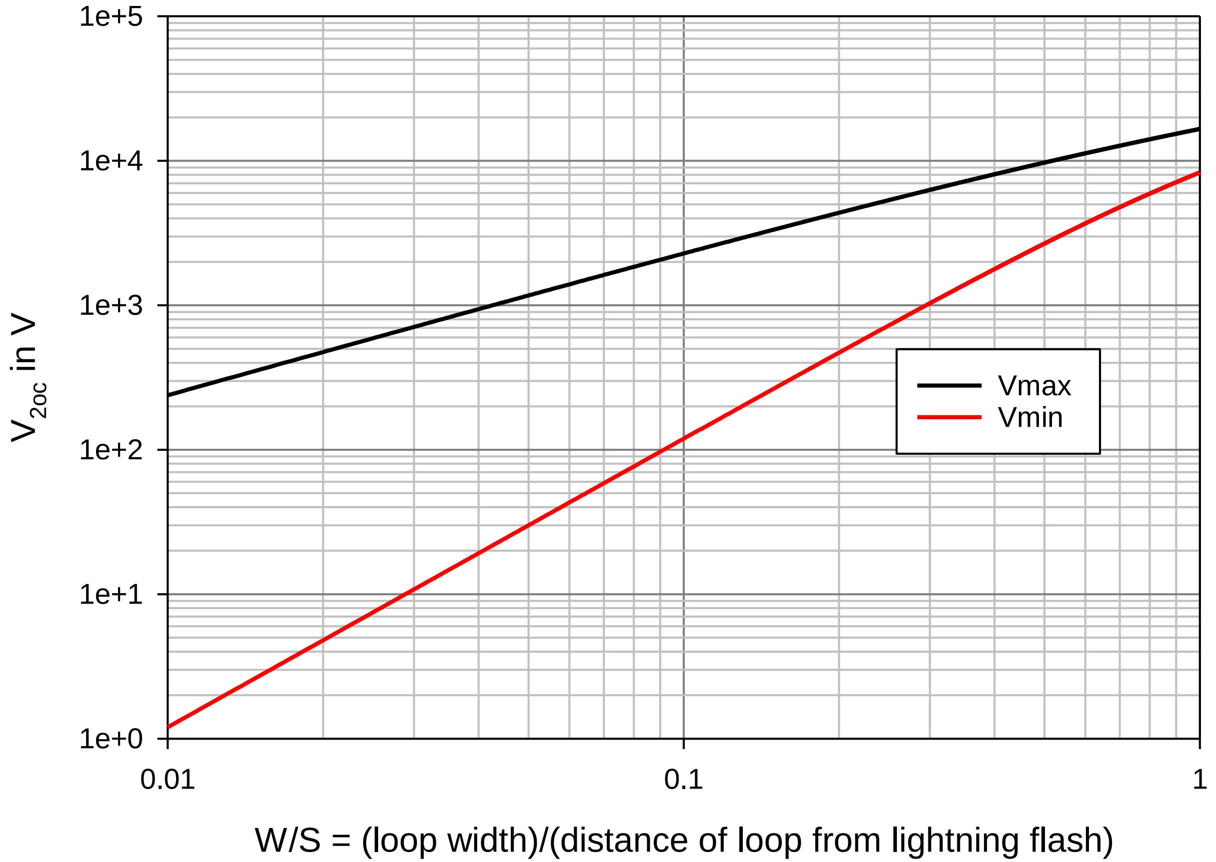
Going on…

This figure is a plot of equations (8a) and (8b) normalized to 1 kA/us and h = 1 m.



To find V_{2oc} , multiply the y-axis scale by the chosen di/dt and chosen loop height h.

So for a example for a median di/di of 40 kA/µsec from CIGRE TB549 Table 3.5 [2] and a 3 m high loop, we would have the plot below, which for this particular case shows that a V_{2oc} in the 1 kV to 10 kV range is possible.



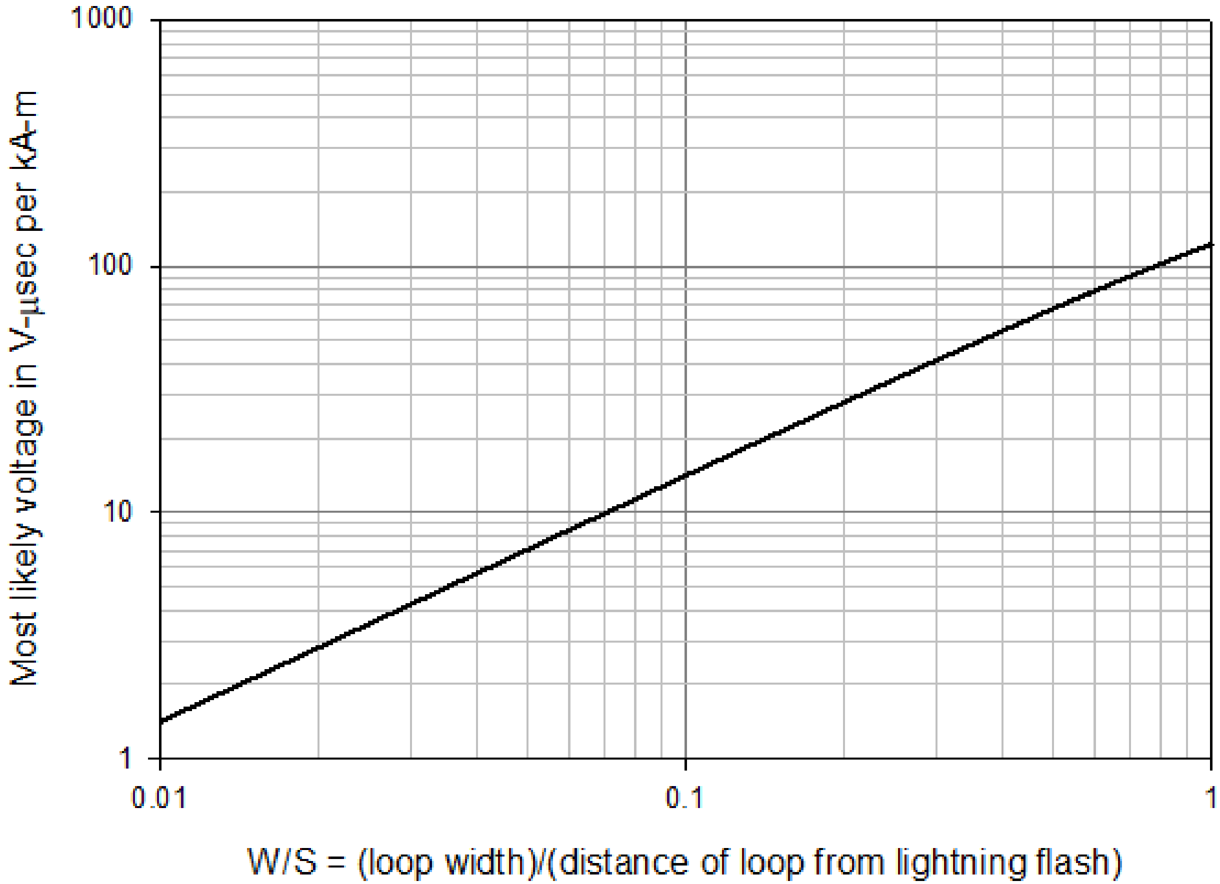
Observations:

- When θ = 0^o we have the case usually presented in discussions of induction. This case corresponds to the worst-case loop orientation, which is generally unlikely.
- For an environment with no prominent lightning attractors (e.g. towers or clumps of tall trees) any value of θ from 0^o to 90^o is equally likely, so the best case of θ = 90^o is just as likely as the worst case of θ = 0^o.

So to answer the question posed in the beginning, the reason why induced voltage predictions are often too high is that the generally assumed worst-case orientation of the loop with respect to the lightning flash B field rarely occurs. As the calculations show, a more likely value of loop orientation will result in a lower predicted voltage.

If the worst-case induced voltage is unlikely, what is a more reasonable prediction?

For an open field, the most likely value of θ is the mid-point or 45°. A plot of this case is shown below (normalized to a loop 1 m high and a di/dt of 1 kA/µsec).

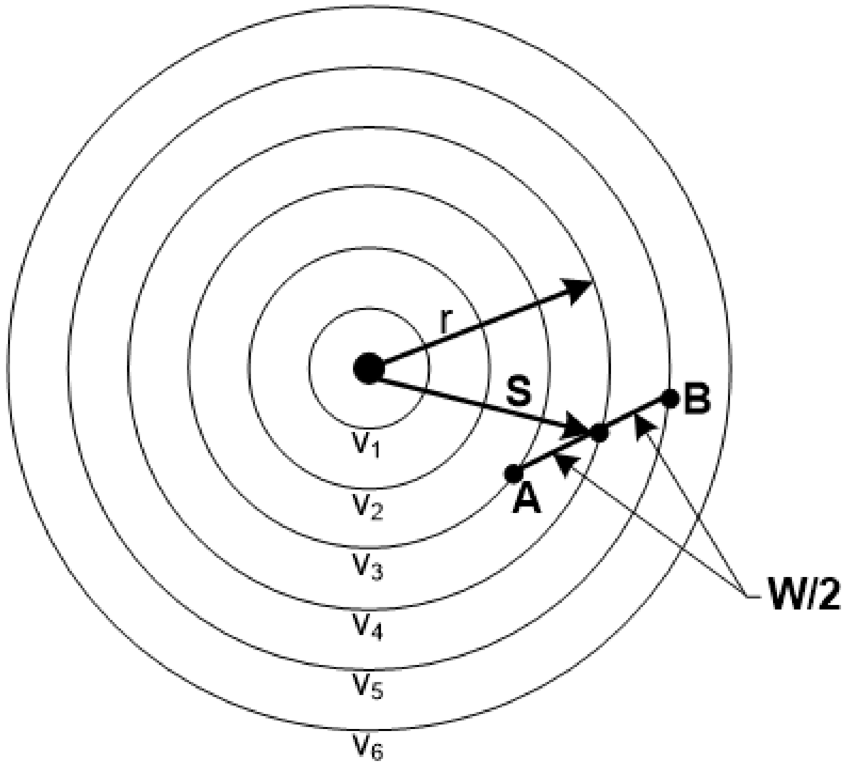


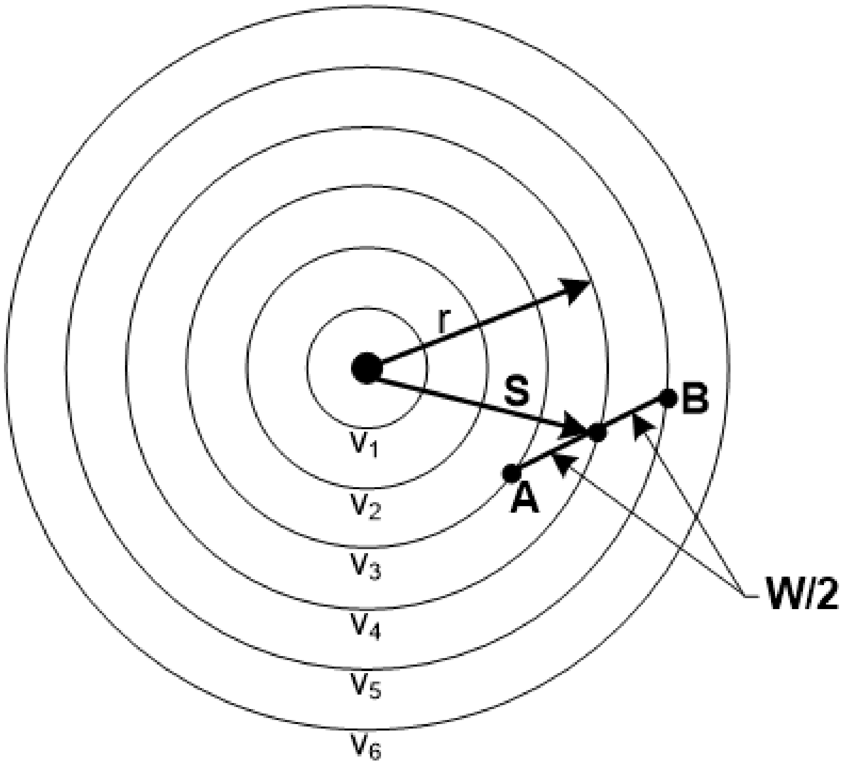
Depending on the value of W/S and the surge di/dt, the plot on the last slide shows that something less than 6 kV is a reasonable value for V_{2oc}. Compare this with the up to 40 kV predicted for a worst-case.

Calculation of combined GPR and induction Voltage

If the installation under consideration has grounds at both ends, then the voltage difference between the ground rods due to GPR needs to be added to the induction voltage. So we need to calculate V_{GPR}.

The Figure below shows the V_{GPR} decrease with distance from a lightning strike, assuming a uniform ground. It also shows a loop having a width W located between grounds at points A and B, and located at a distance S from the lightning strike point.



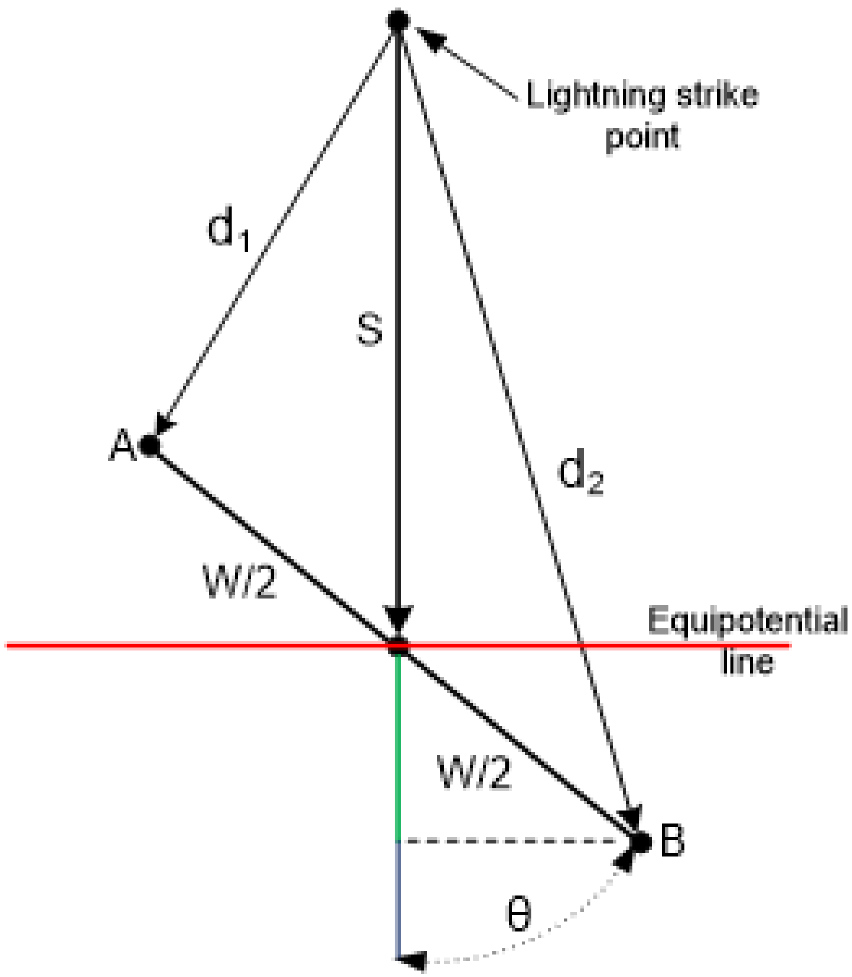


V_{GPR} in a uniform environment is given by

$$V_{GPR} = \frac{\rho I}{2\pi r} \qquad (9)$$

where ρ is the resistivity of the ground in ohm-m.

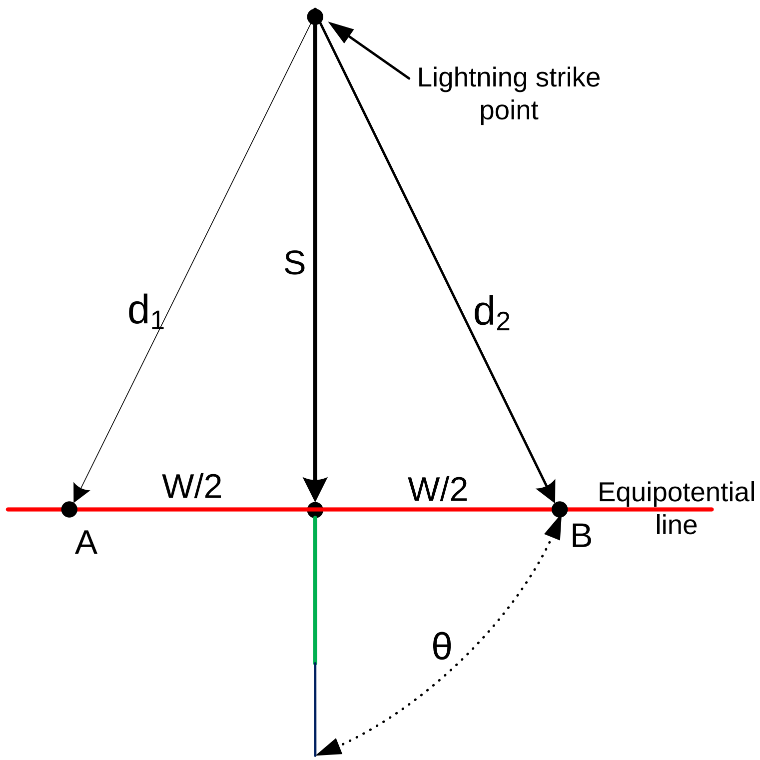
Now again we need to consider geometry.



So similarly to what was done for the B-field, the figure at left is a top view of the figure on the previous slide. It shows the geometry we're dealing with.

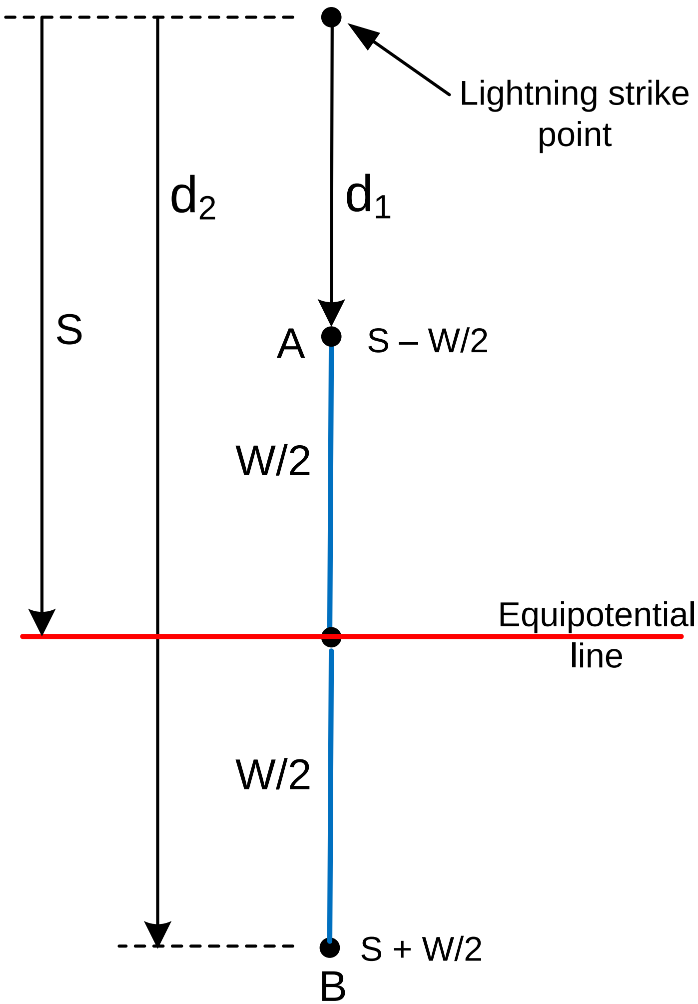
Considering the geometry, V_{GPR} between the ends of the ICT loop is

$$V_{GPR} = \frac{\rho I}{2\pi}\left[\frac{1}{d_1} - \frac{1}{d_2}\right] \quad (10)$$



When both points A and B are on the same equipotential line, $d_1 = d_2$, and

$V_{GPR} = 0$ ($\Theta = 90^o$)



The highest value of V_{GPR} is when points A and B fall on an extension of S, given by

$$V_{GPR} = \frac{\rho I}{2\pi}\left[\frac{1}{S-\frac{W}{2}} - \frac{1}{S+\frac{W}{2}}\right] \quad (\Theta = 0^o) \qquad (11)$$

Rewriting equation (11)

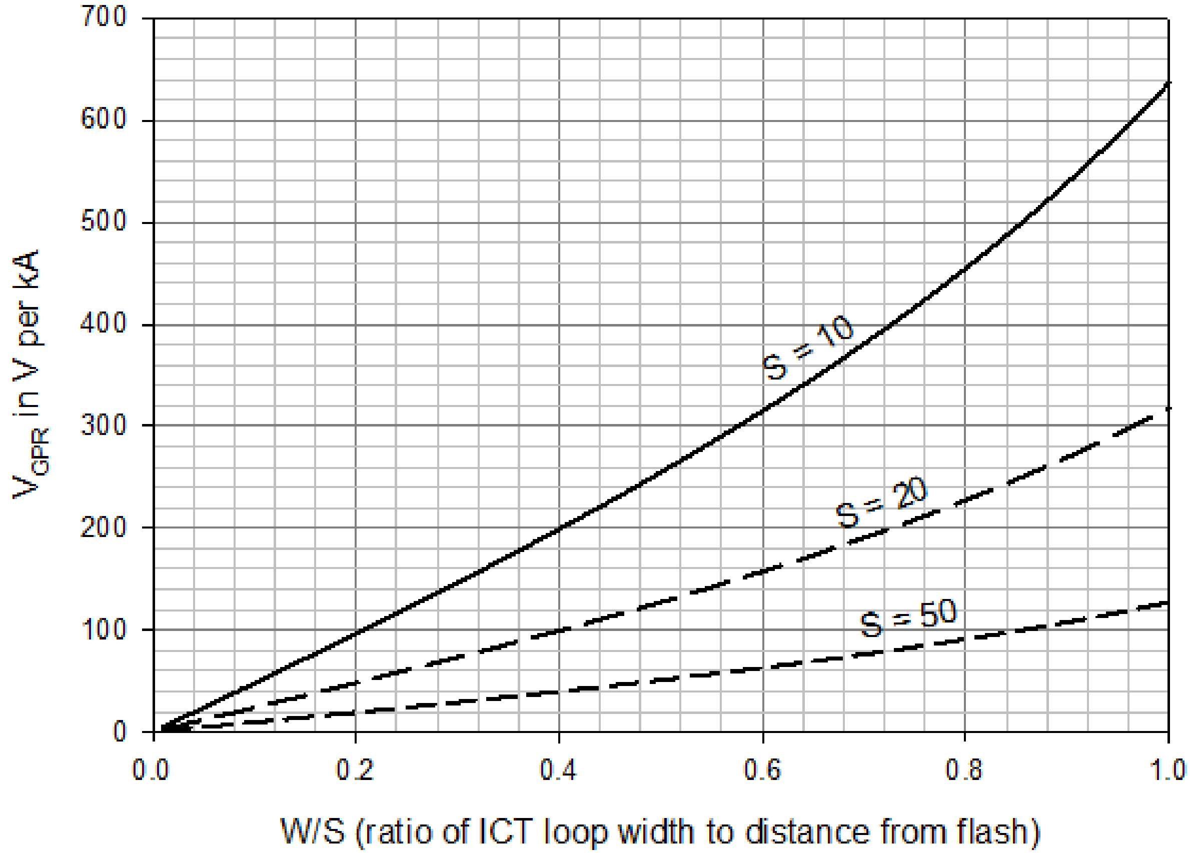
$$V_{GPR} = \left[\frac{2\rho I}{\pi S}\right]\left[\frac{\frac{W}{S}}{4-\left(\frac{W}{S}\right)^2}\right](\Theta = 0^{o})$$

So for a representative ground resistivity of 300 ohm-m

$$V_{GPR} = \frac{1.91x10^5}{S}\left[\frac{\frac{W}{S}}{\left[4-\left(\frac{W}{S}\right)^2\right]}\right] \quad \text{V/kA (maximum } V_{GPR}) \qquad (12)$$

where V_{GPR} has been normalized to 1 kA.

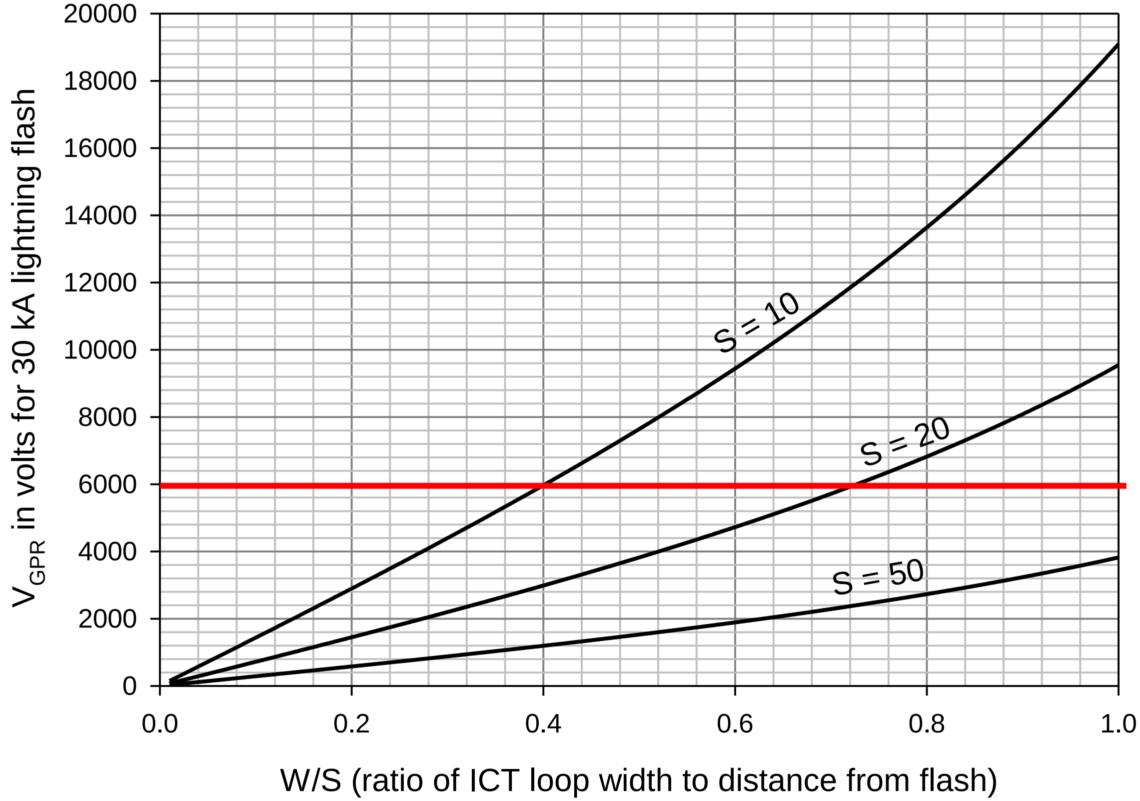
In the Figure below, the worst-case V_{GPR} ($\Theta = 0^{o}$) from equation (12) is plotted as a function of W/S for several values of S.



To get V_{GPR} multiply the y-axis value by the lightning flash current in kA.

Now analogous to Figure 8, V_{GPR} can be plotted as a function of θ for various values of W/S. The result is shown in Figure 11.

For example, for a 30 kA lightning flash the previous Figure can be replotted as shown Below:



For example, for this case a V_{GPR} in excess of 6 kV is possible, so you would want your isolation barrier to withstand at least 6 kV.

The voltage due to induction can either add or subtract from the GPR, depending on whether the lightning return stroke is going up or down. For the most common upward return stroke the voltage from induction adds to the voltage from GPR.

This combined voltage might cause failure, whereas either one alone would not.

For example, from the plot of reasonable induced voltage, something up to 6 kV would be expected. Add this to the possible 6 kV shown on the plot for GPR voltage, and the combined voltage could exceed 10 kV.

In this example systems designed with 6 kV isolation would likely survive either the induction or the GPR voltage, but not both combined.

Current calculations

Induced current

Induced common-mode current will flow in the ICT loop if there is some kind of connection that closes the loop, e.g. an Ethernet Smith termination or the operation of an SPD. The induced current is given by the induced voltage divided by the loop impedance *Z:*

$$I_2 = \frac{M}{Z}\frac{di}{dt} \qquad (12)$$

where Z is composed of the total circuit resistance R_S and the circuit inductance L_S. The worst case is probably the operation of an overvoltage device, in which case Z would be dominated by L_S (e.g. as assumed in ITU-T K,67,annex I calculation).

For the worst-case Z and Ө = 0º, substitute equation (8a) into equation (12) to get:

$$I_{2max} = \left(\frac{200h}{L_S}\right)\frac{di}{dt}\left[ln\left(1+\frac{W}{S}\right)\right] \text{ Amps} \qquad (13a)$$

Similarly for the worst case Z and Ө = 90º, substitute equation (8b) into equation (12) to get

$$I_{2min} = \left(\frac{200h}{L_S}\right)\frac{di}{dt}\left\{ln\left[1+\left(\frac{W}{S}\right)^2\right]^{0.5}\right\} \text{ Amps} \qquad (13b)$$

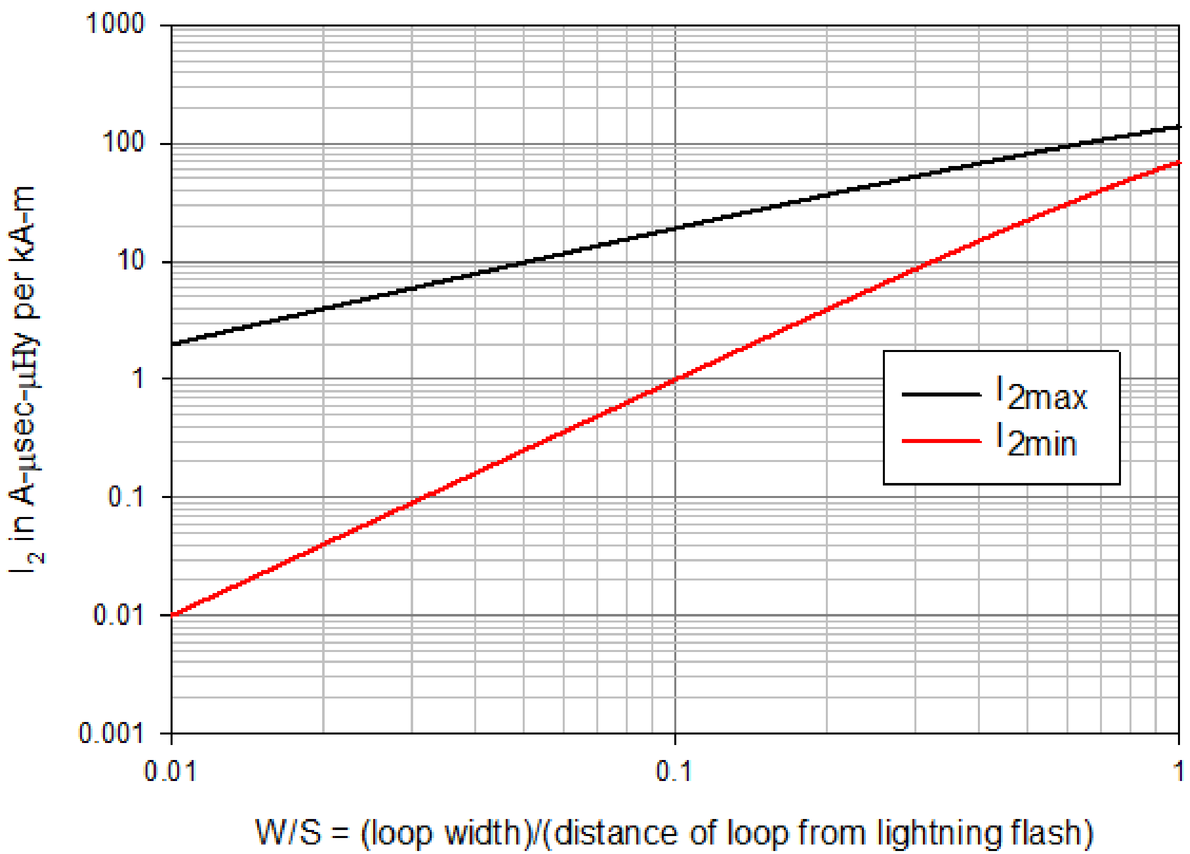
In both equations (13a) and (13b) h is in m, di/dt is in kA/µs, and L_S is in µH.

Normalizing equations (13a) and (13b) to h = 1 m, L_S = 1 µH, and di/dt =1 kA/µs (so we can plot it) we get:

$$I_{2max} = 200ln\left(1 + \frac{W}{S}\right) \text{ Amp-µs-µH per kA-m} \quad (14a)$$

$$I_{2min} = 200ln\left[1 + \left(\frac{W}{S}\right)^2\right]^{0.5} \text{ Amp-µs-µH per kA-m} \quad (14b)$$

Equations (14a) and (14b) are plotted below. To find I_2, multiply the y-axis value by h in m, di/dt in kA/µs, and divide by L_S in µH.



An example of a possible worst-case is $\Theta = 0^o$, $h = 3$ m, $L = 43$ µH, W/S = 1 and from CIGRE TB549 Table 3.5, di/dt = 100 kA/µs, for which $I_2 = 977$ A.

More likely values of W/S and θ would result in lower induced currents of perhaps 300 A. A less extreme di/di would further reduce the induced current. But currents on that order might still be a problem.

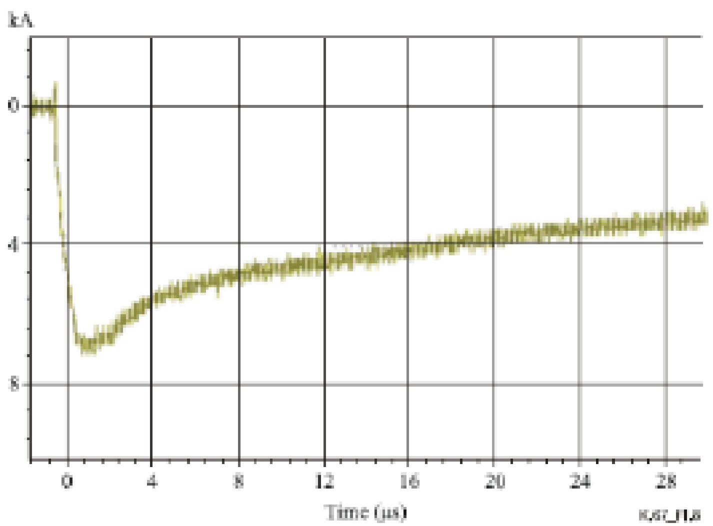
I^2T caused by Induced current

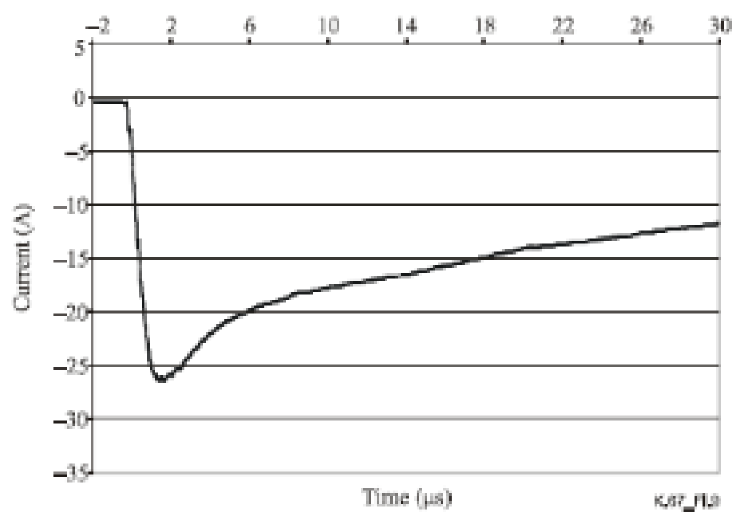
Generally we're less interested in current than I^2T, because I^2T is what blows fuses or heats up and potentially destroys resistances in the circuit.

In order to calculate I^2T we need to know what the induced current waveform looks like, because to get I^2T the current is integrated over the whole waveform.

As an aid to visualizing the waveform we can look at the experimental results in ITU-T K.67

Lightning and induced current waveshapes adapted from that experiment, are shown below. They look similar, suggesting that the induced current waveshape is the same as the lightning waveshape (which would be expected if the lightning-loop arrangement works like an air core transformer)





So assuming that the induced current $I_2(t)$ has the same waveshape as the lightning current, and is a double-exponential

$$I_2(t) = I_{2peak}\left(e^{-at} - e^{-bt}\right) \qquad (15)$$

Then $I^2T = I_{2peak}^2 \int_0^{\infty}\left(e^{-2at} - 2e^{(a+b)t} + e^{-2bt}\right)dt$ (16)

Doing the integration,

$I^2T = I_{2peak}^2 \left[\frac{2e^{-(a+b)t}}{a+b} - \frac{be^{-2at}+ae^{-2bt}}{2ab}\right]_0^{\infty}$, which evaluates to:

$$I^2T = I_{2peak}^2 \left[\frac{b^2-a^2}{2ab(a+b)}\right] \ \mathrm{A^2s} \qquad (17)$$

An estimate of I_{2peak} can be obtained from equation (14a) or (14b), or the plot of I_{2peak} vs. W/S

For the general case, I^2T can be estimated from equation (17).

As an example case, assume (as was done previously) that the lightning surge is the 30 kA 5.5/75 from CIGRE TB549. Then $a = 1.0x10^4$ and $b = 8.1x10^5$, so in equation (17)

$$\left[\frac{b^2-a^2}{2ab(a+b)}\right] = 4.94\text{x}10^{-5},$$

and $\mathrm{I}^2\mathrm{T} = 4.94\text{x}10^{-5}\mathrm{I}_{2\mathrm{peak}}^2$ (18)

Now suppose we would like to know if the I^2T due to induction would blow a 1.25 A telecom fuse, which typically is rated at an I^2T of 15 -17 A^2s (when applied for 10 msec or less).

The plot of I_{2peak} vs the loop orientation angle θ can be used to get a possible worst-case estimate of I_{2peak}, as well as more reasonable values. So for a possible worst-case estimate (from a previous example), I_{2peak} = 977 A. Then using equations (17) and (18), I^2T = 46 A^2s, which would blow the fuse.

For more reasonable values of θ and W/S , I_{2peak} might be 300 A, for which the corresponding I^2T = 4.4 A^2s, which wouldn't blow the fuse.

The I^2T calculation has many variables, and assumes no surge mitigation has been done. Depending on the values of the variables, the I^2T due to induction can range from high and likely to cause damage to low and unlikely to cause damage.

So currents due to induction alone may or may not cause problems. What about GPR?

The current I_5 resulting from a GPR can be calculated as shown in a presentation from the 2016 PEG meeting [3], where it was shown that

$$I_5(t) = I_{peak}\left(e^{-at} - e^{-bt}\right)G_{TERM} \qquad (19)$$

Where G_{TERM} is a geometric factor that can be estimated using the procedure in [3]. With that in mind, equation (17) can be modified to estimate $I_2^2 T$ as

$$I_2^2 T = \left[G_{TERM} I_{peak}\right]^2 \left[\frac{b^2 - a^2}{2ab(a+b)}\right] \qquad (20)$$

Using the same conditions as were used for induced current,

$$\frac{b^2 - a^2}{2ab(a+b)} = 4.94x10^{-5}.$$

An example calculation of G_{TERM} from [3] assumed the resistance of each ground rod is 40 ohms. As in the case of induced current, assume a possible worst-case of S = 10 m, W = 10 m and $\theta = 0^{o}$, for which from [3] gives $G_{TERM} = 1.35 \times 10^{-2}$. Putting these numbers in equation (20) with $I_{peak} = 30$ kA, $I_2^2 T = 8.1$ A^2s.

Again this value of I^2T is influenced by the choice of values for the many variables involved. And the I^2T from GPR may need to be added to that from induction.

So the question of whether the I^2T due to a nearby lightning strike is too high or too low basically needs to be answered on a case-by-case basis.

Summary

By including loop orientation, what the calculations in this presentation do is to put worst-case and best-case bounds on the lightning-caused voltage and currents that could be due to induction, GPR, or both combined – something that is seldom, if ever, done. In fact the calculations presented in the literature are only for the worst case; and in practice the voltages and currents will be somewhere between the best case and the worst case.

Summary

Why would we care? Well designing common-mode protection for the upper bound (worst case) might not be cost-effective. Designing protection for the lower bound (best case) is a possible solution, but probably not a good one.

The equations and plots given here offer a way to estimate a reasonable case, which might be the best solution for protection against the effects of induction and GPR.

References

[1] ITU-T K.67, Expected surges on telecommunications and signaling networks due to lightning, Geneva, Switzerland: International Telecommunications Union, 2006.

[2] CIGRE Working Group C4.407, "Lightning Parameters for Engineering Applications," CIGRE TB 549, 2013.

[3] A. Martin, "Lightning Induced GPR Characteristics and Comments," in The Alliance for Telecommunications Industry Solutions Protection Engineers Group Conference, March 13 - 15, Huntsville, Alabama, 2012.

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Questions?