Effects of Lightning on ICT Circuits……
Induction and GPR/GCR

PEG CONFERENCE

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GGG

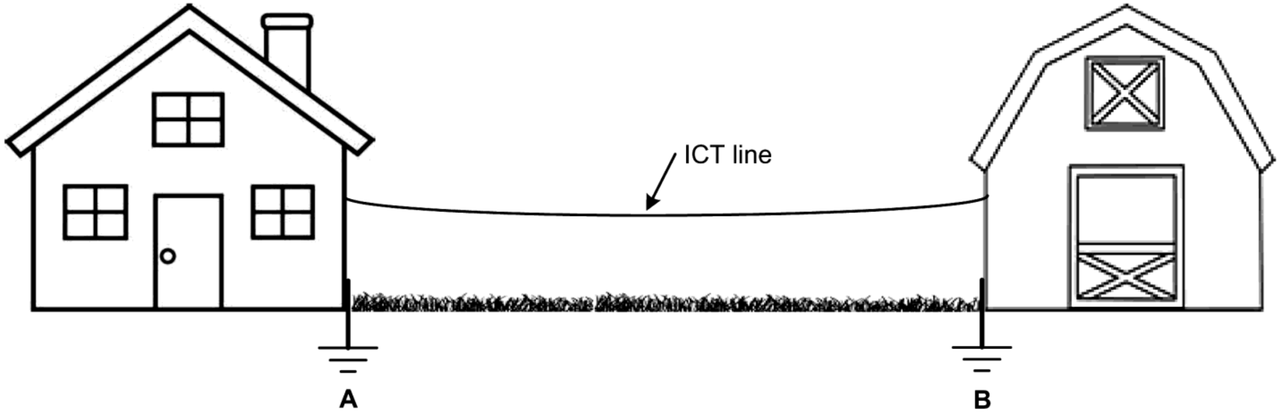
Generally the effect of lightning we worry about most is damage, which can occur in 4 ways:

- By induction from a nearby strike
  - In a system with more than one ground
    - By flashover due to ground potential rise (GPR) in a high Z circuit
    - By the heating effects of ground current rise (GCR) in a low Z circuit
- By a direct strike

Let's consider an ICT loop that is probably the most exposed to the effects of lightning – one that runs between structures.

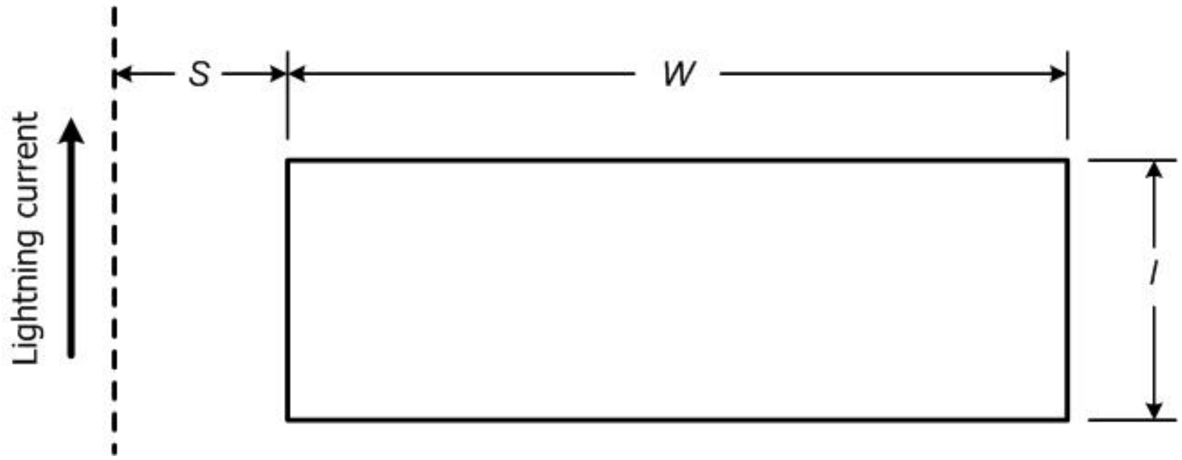
The Model

Assume that we have two structures with grounds at point A and point B; and assume that there is an ICT line running between the two structures. A loop is then formed by the ICT line, the ICT circuit to ground at each end of the line, and the ground resistance.



Induction from a nearby strike

We want to calculate the current induced in the loop by lightning flash current flowing in the lightning channel represented by the dashed line in the figure below



In the figure, S is the distance of the flash from the loop, *W* is the distance between the ground at Point A and the ground at Point B, and ℓ is the height of the ICT wire above ground

Induction from a nearby strike

So how much current does the flash induce? Well the induced current is governed by the mutual inductance *M* between the channel and the loop.

To calculate *M*, we start by calculating the magnetic field *B* through the rectangular loop. Using Ampere's law the magnetic field at a distance *r* away from the lightning flash is

$$B = \frac{\mu_0}{2\pi r}$$

Induction from a nearby strike

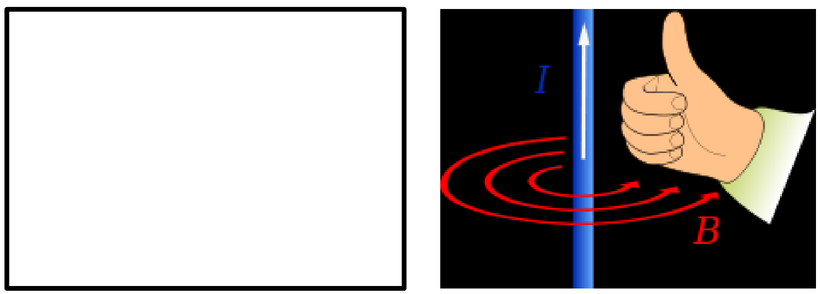
Knowing *B* the next step is to calculate the total magnetic flux Φ_B as shown below, where the differential loop area $\overrightarrow{dA} = l\overrightarrow{dr}$ ($\vec{r}$ being the distance and direction to the loop from the lightning flash).

$$\Phi_B = \int \overline{B} \cdot d\overline{A} = \frac{\mu_0 Il}{2\pi} \int_S^{S+W} \frac{dr}{r} = \frac{\mu_0 Il}{2\pi} \ln\left[\frac{S+W}{S}\right]$$

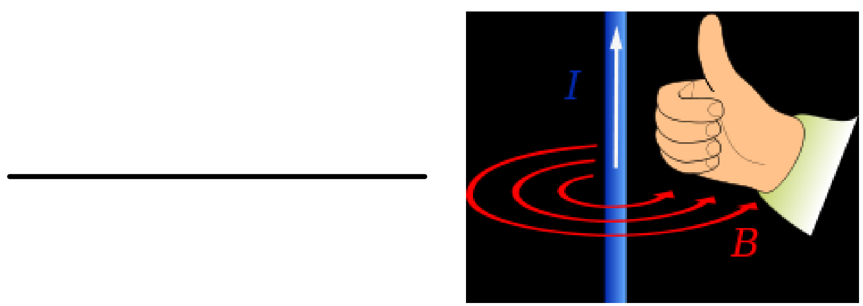
$\vec{B} \cdot \overrightarrow{dA}$ is a vector product. A note on vectors....

Induction from a nearby strike

By the right-hand rule, current flow as shown results in a B-field in the direction of the fingers. So if the loop is oriented as shown, the coupling to the loop is maximized:



If the loop is rotated 90º the coupling is minimized:



Induction from a nearby strike

The vector product takes into account the angle of the loop with respect to the B field. The flux Φ_B is maximized when the angle is zero (top picture in the last slide), so that $\vec{B} \cdot \overrightarrow{dA} = BdA$. In that case the maximum value of Φ_B is :

$$\Phi_B = \int \overline{B} \cdot d\overline{A} = \frac{\mu_0 Il}{2\pi} \int_S^{S+W} \frac{dr}{r} = \frac{\mu_0 Il}{2\pi} \ln\left[\frac{S+W}{S}\right]$$

Induction from a nearby strike

Now knowing Φ_B the maximum mutual inductance is the maximum flux divided by the current:

$$M = \frac{\Phi_B}{I} = \frac{\mu_0 l}{2\pi} \ln\left[\frac{S+W}{S}\right]$$

Now to get an estimate for *M*, Let the height of the loop ℓ be 3 m, the distance *W* between the two structures 30 m; and assume the lightning flash is *S* = 30 m away.

In this case *M* = 1.4 µHy

Induction from a nearby strike

Loop current is generally very small, since the resistance to ground of the ICT circuits is usually very large, unless the insulation breaks down. To see if enough voltage is generated to break down the insulation, the voltage developed across a very high resistance can be estimated by assuming the lightning-stroke current is a double-exponential

$$i(t) = I_{peak}\left(e^{-at} - e^{-bt}\right)$$

Then the open-circuit voltage *V(t)* is

$$V(t) = M\frac{di}{dt} = MI_{peak}\left(-ae^{-at} + be^{-bt}\right)$$

Induction from a nearby strike

Now let lightning be the median 30 kA 5.5/75 surge from CIGRE TB549 Table 3.5 [1]. Then in the expression for *V(t)*, (repeated below)

$$V(t) = M\frac{di}{dt} = MI_{peak}\left(-ae^{-at} + be^{-bt}\right)$$

$a = 1 \times 10^4$, $b = 8.1 \times 10^5$, and $I_{peak} = 30$ kA. As previously calculated, $M = 1.4$ µHy. With these numbers the resulting peak voltage is about 33 kV, which is likely to be enough to cause insulation breakdown.

Induction from a nearby strike

If insulation breakdown occurs, the impedance Z of the loop becomes the combination of resistance between the two grounds plus whatever resistance is present in the ICT circuits, and the inductance of the ICT line.

Given that Z, the loop current $I_W(\omega)$ as a function of frequency is:

$$I(\omega) = \frac{V(\omega)}{Z}$$

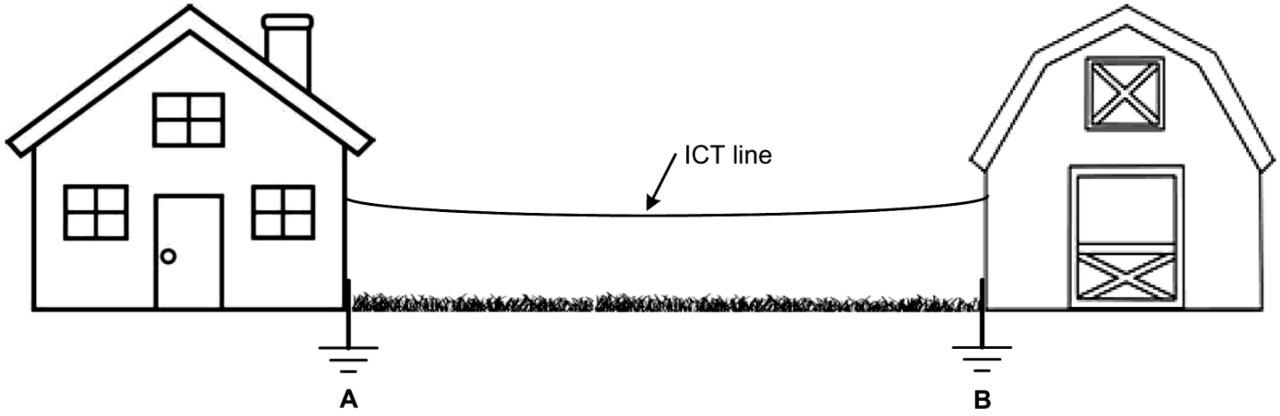
Where *V(ω)* is the frequency representation of *V(t)* calculated earlier

Induction from a nearby strike

Compared to the other resistances in the circuit, the resistance of the ICT line is negligible, so Z =R_S +$j\omega L_C$, where R_S is the sum of the resistance R_C of the ICT circuit to ground at each end of the cable, and the resistance between the two grounds.

Induction from a nearby strike

Referring to the figure for the model (reproduced below), assume the grounds at A and B are rods having a length *L* and radius *a*; and assume they are spaced a distance *W* apart, in soil of resistivity *ρ*.



Induction from a nearby strike

With those assumptions we can calculate the resistance *R* between the rods by using the expression from IEEE Std. 142-1991:

$$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} - 1\right) + \frac{\rho}{4\pi W}\left(1 - \frac{L^2}{3W^2} + \frac{2L^4}{5W^2}\ldots\right)$$

To get an estimate of the resistance of the two grounds, assume *ρ* = 300 ohm-m, the spacing between grounds *W* = 30 m (the distance between the 2 structures), the length of the grounds *l* = 2 m, and the diameter of the ground rods *a* = .01 m. These numbers give R = 81 ohms.

Induction from a nearby strike

To get an estimate of the inductive component of Z, assume that the ICT line is a 30 m length of two #22 AWG wires in parallel, for which the inductance is about 33 µH.

Assuming the same median 30 kA 5.5/75 surge from CIGRE TB 549 Table 3.5, the maximum value of the reactance ($j\omega L_C$) is 0.29 ohms at 8.9 kHz, very much less than R_S. So $j\omega L_C$ can be neglected, and $Z = R_S$.

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Induction from a nearby strike

With these observations in mind we can go to the previous expression for *V(t)*

$$V(t) = M\frac{di}{dt} = MI_{peak}\left(-ae^{-at} + be^{-bt}\right)$$

And then since $I_W(t) = \frac{V(t)}{R_S}$

$$I_W(t) = \frac{MI_{peak}}{R_S}\left[be^{-bt} - ae^{-at}\right]$$

Induction from a nearby strike

Now using the numbers previously assumed (including a ground resistance of 81 ohms), we can calculate and plot the peak loop current as a function of ICT circuit resistance, which we'll do shortly.

However what we really want to know is how much energy is deposited in the ICT circuits, because that causes them to heat up and possibly be destroyed. That energy, *J* (the time integral of the power) is:

$$J = R_C \int_0^\infty i_W(t)^2 \, dt$$

Induction from a nearby strike

From the equation for $I_W(t)$

$$i_W(t)^2 = \left[\frac{MI_{peak}}{R_S}\right]^2 \left[b^2 e^{-2bt} - abe^{-(a+b)t} + a^2 e^{-2at}\right]$$

So that doing the integral from the previous slide

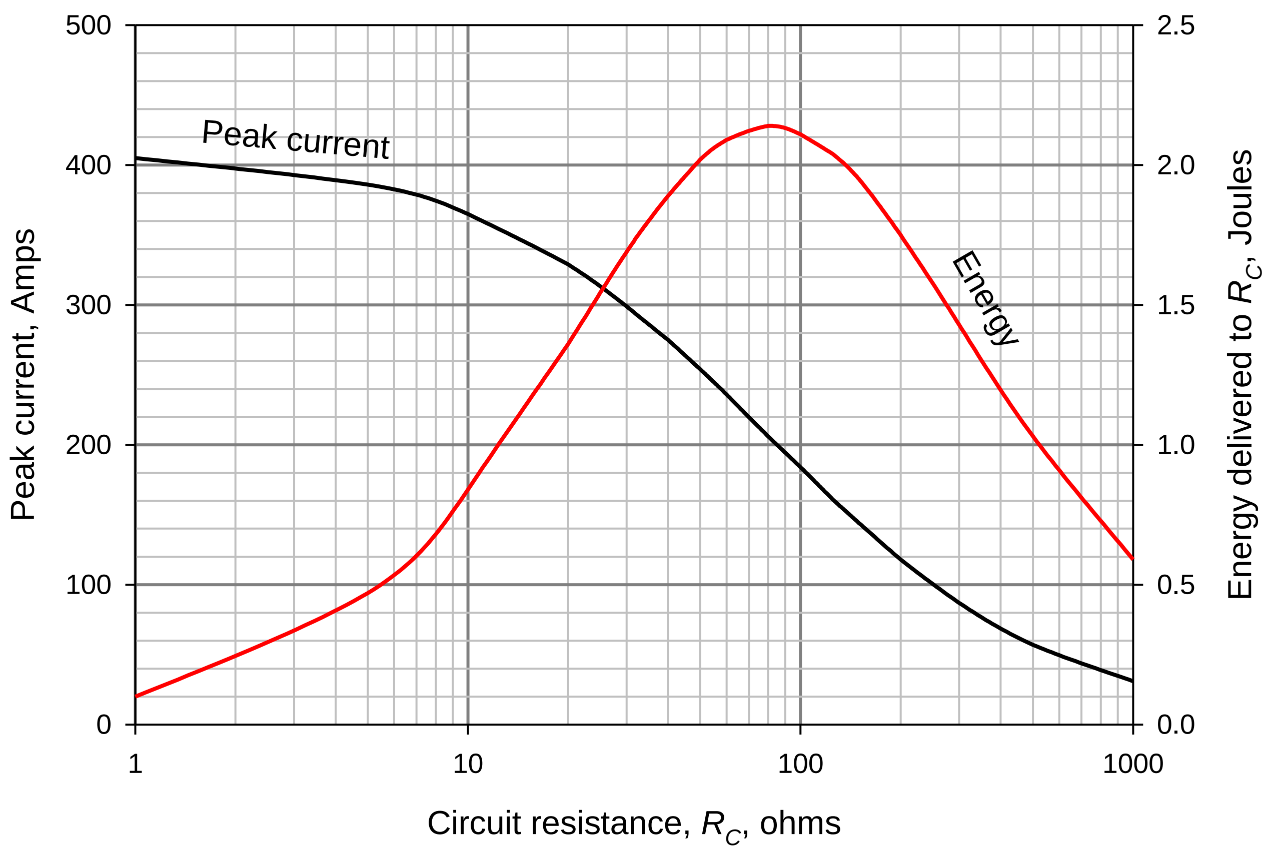
$$J = R_C \left[\frac{MI_{peak}}{R_S}\right]^2 \left[\frac{ab}{a+b} e^{-(a+b)t} - \frac{a}{2} e^{-2at} - \frac{b}{2} e^{-2bt}\right]_0^\infty$$

Which evaluates to

$$J = R_C \left[\frac{MI_{peak}}{R_S}\right]^2 \left[\frac{a^2 + b^2}{2(a+b)}\right]$$

Induction from a nearby strike

This last equation and the one for $I_W(t)$ for the case considered can be plotted as



Induction from a nearby strike

Once we know the amount of energy deposited in a device, we can calculate its temperature rise above ambient (assuming it's adiabatic, *i.e.* no heat loss) from:

$$\Delta T = \frac{J}{c_p m} = \frac{R_C}{c_p m}\left[\frac{MI_{peak}}{R_S}\right]^2 \left[\frac{a^2 + b^2}{2(a+b)}\right]$$

Where ΔT is the temperature rise in °C, c_p is the heat capacity in Joules/(gram-°C), and *m* is the mass in grams. For silicon and ceramic-based devices, the heat capacity is around 0.85 ±0.05 J/g°C.

As an example, from the plot, a 75 ohm chip resistor with a mass of 0.1 g would have 1 J deposited in it, resulting in a ΔT of 11 °C

Induction from a nearby strike

The previous plot is only for a first stroke. In reality a lightning flash is composed of a first stroke and typically 4 subsequent strokes. The subsequent strokes contribute heating energy to any resistances in the circuit, so it is of interest to estimate how much energy that is.

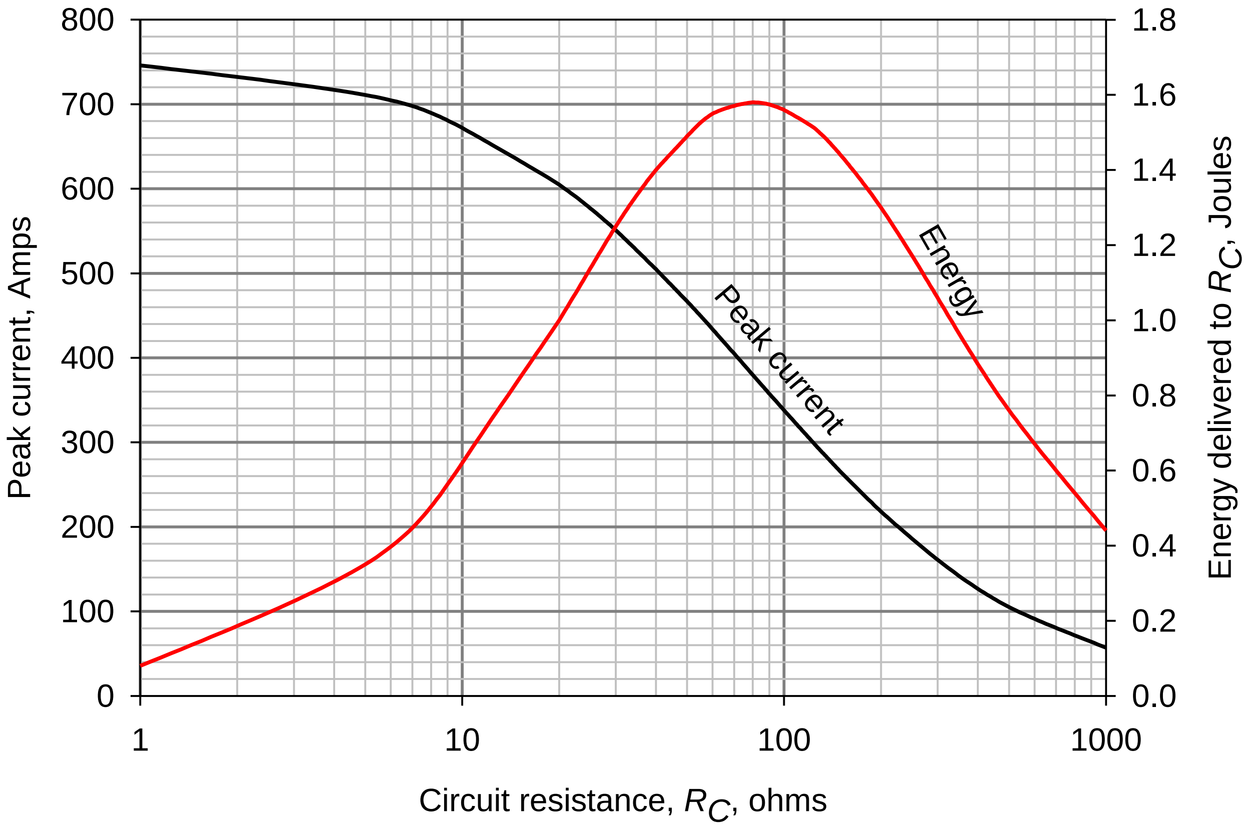
Induction from a nearby strike

From CIGRE TB549 the median subsequent surge is 12 kA 1.2/32, for which in

$$i(t) = I_{peak}\left(e^{-at} - e^{-bt}\right)$$

a **= 2.27x104 and *b* = 3.73x106. With these values along with the previously assumed values for the other variables (including a ground resistance of 81 ohms), the current $I_W(t)$ and the energy *J* for a subsequent stroke can be calculated and plotted.**

Induction from a nearby strike



Current induced in an ICT circuit for the case considered by a typical 12 kA 1.2/32 subsequent stroke 30 m away, and the resulting energy in R_C.

Peak Current is higher than in the previous slide because it depends on M(di/dt), which is greater for a subsequent surge than for a first stroke, which more than compensates for the lower stroke current.

Induction from a nearby strike

To continue the previous example, an Ethernet circuit with 75 ohm terminations at each end would have about 1.4/2 = 0.7 J deposited in each resistor, due to a single subsequent stroke.

The energy in one subsequent surge might not be dissipated before the next occurs. Assuming that to be the case, for the 4 typical subsequent surges, the maximum amount of energy deposited in a 75 ohm Ethernet termination might be 4x0.7 = 2.8 J. In a worst case the energy from the subsequent surges adds to that from the first stroke to give a total of 3.8 J, causing a temperature rise of 42 ^{o}C.

Induction from a nearby strike

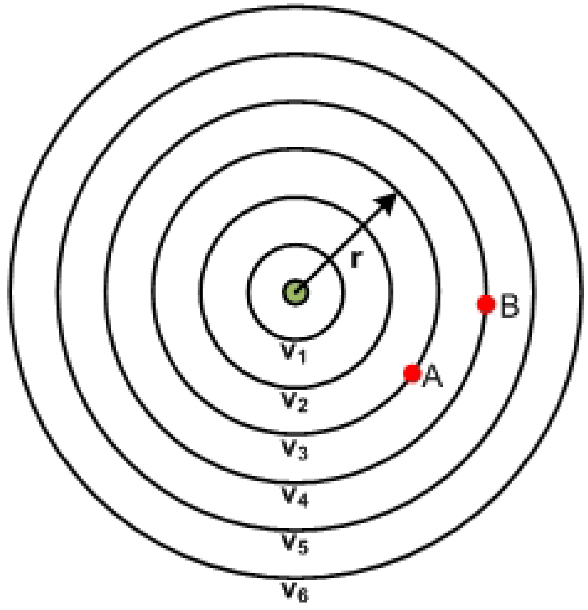
The amount of energy deposited in R_C might be more or less than those just calculated, depending on the waveform of the lightning flashes and the circuit characteristics. For example, if the lightning strike is 10 m away instead of 30 m, the total worst case energy goes to 15.4 J, for a temperature rise of 170 ^{o}C.

The result of all this effort is that temperature rise in the circuit resistances is not likely to be excessive, and thus any damage from induction would most likely be due to flashover, not the heating effects of current.

The energy due to induction will add to that due to ground current rise (GCR), which we will consider next.

Ground potential rise (GPR) and ground current rise (GCR)

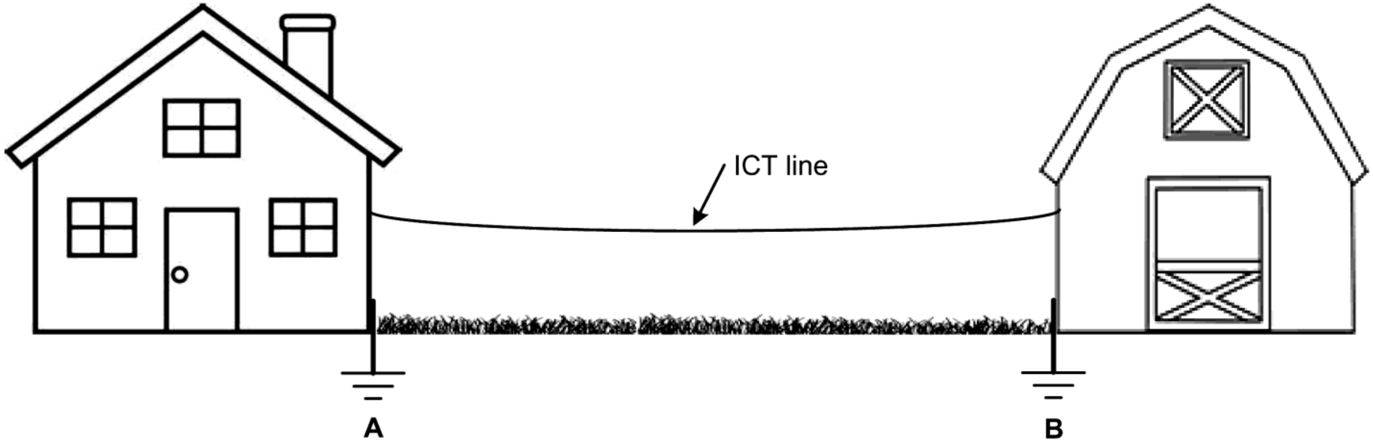
As a review, In the case of a uniform earth, the current density from a lightning flash spreads out from the point of contact of the flash. The voltage created by the spreading flash current density decreases as the distance from the flash increases, as illustrated below. The result is that the ground potential at a point closer to the flash, e.g. point A, is greater than the ground potential at a more remote point B, hence there is a difference in potential due to a GPR between points B and A.



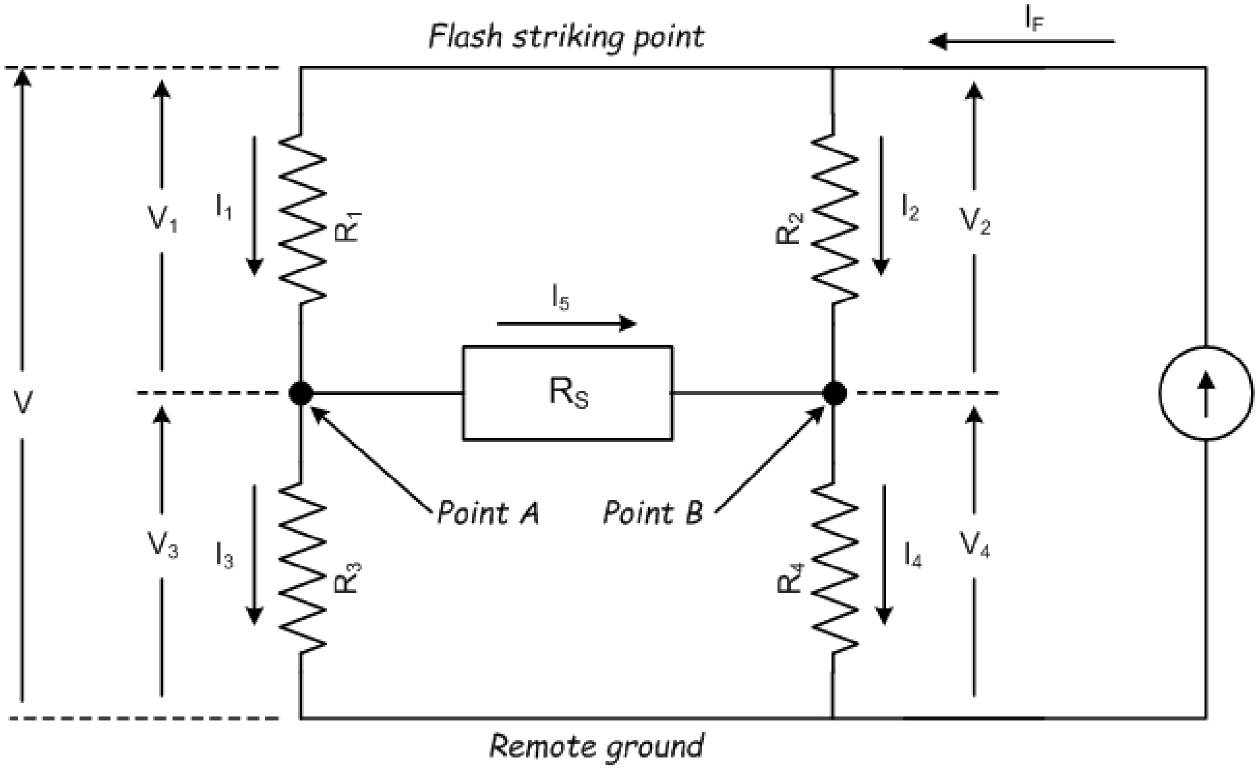
$$V_1 > V_2 > V_3 \ldots$$

Ground potential rise (GPR) and ground current rise (GCR)

Referring to the model for the induction case (reproduced below), an equivalent circuit for the GPR/GCR case can be constructed as shown on the next slide



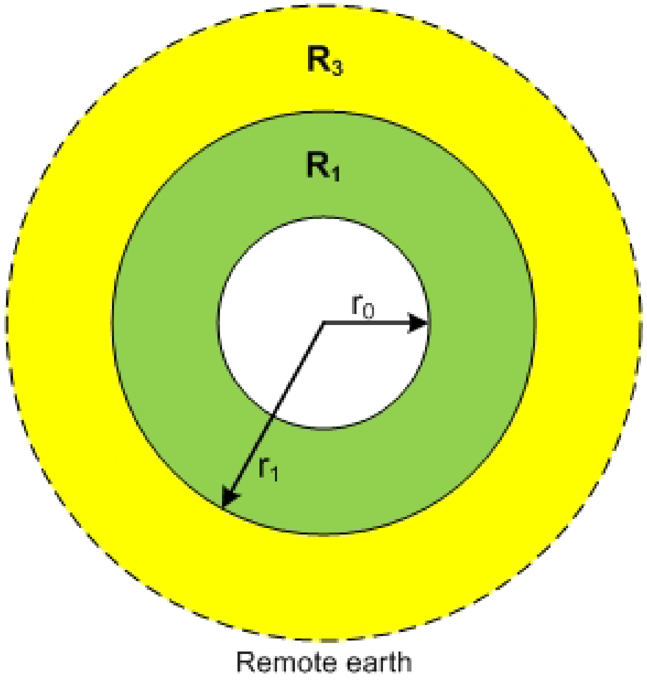
Ground potential rise (GPR) and ground current rise (GCR)



R_1 is the resistance of the earth between the flash striking point and point A, R_2 is the resistance of the earth between the flash striking point and point B, R_3 is the earth resistance between point A and a remote ground, R_4 is the earth resistance between point B and a remote ground, and R_S is the sum of all resistances between the two ground points. I_F is the current due to the lightning flash.

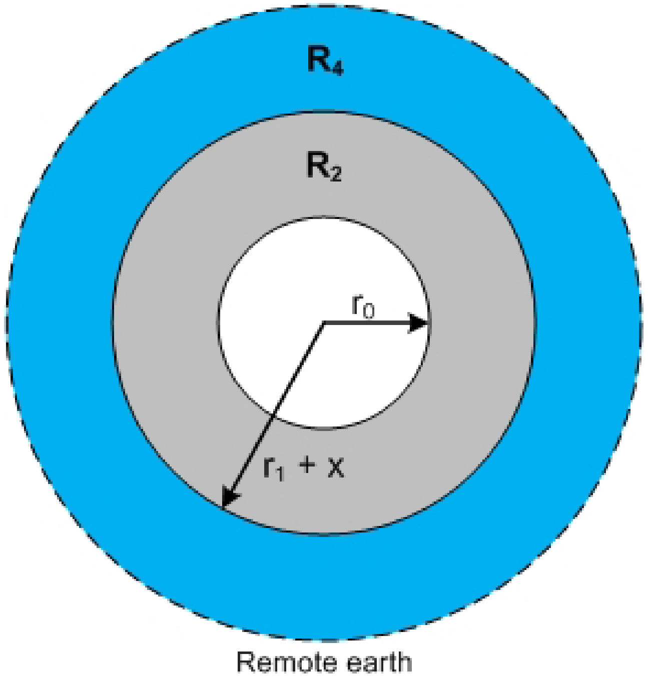
Ground potential rise (GPR) and ground current rise (GCR)

Assuming uniform earth, R_1 is the resistance of the green toroid having an inner radius r_0 of the lightning-strike area; and an outer radius r_1 from the lightning strike point to point A. Similarly R_3 is the resistance of the yellow toroid between r_1 and remote earth.



Ground potential rise (GPR) and ground current rise (GCR)

Similarly, Let x be the distance of the point A ground from the point B ground. Then R_2 is the resistance of the gray toroid between r_0 and $r_1 + x$; and R_4 is the resistance of the blue toroid between $r_1 + x$ and remote earth.



Ground potential rise (GPR) and ground current rise (GCR)

Let ρ be the resistivity of the ground. Then using the guidance of IEEE Std.142:1991, expressions for the (toroidal) resistances just characterized are:

$$R_1 = \frac{\rho}{2\pi}\left[\frac{1}{r_0} - \frac{1}{r_1}\right] = \frac{\rho}{2\pi} G_1 \qquad R_2 = \frac{\rho}{2\pi}\left[\frac{1}{r_0} - \frac{1}{r_1 + x}\right] = \frac{\rho}{2\pi} G_2$$

$$R_3 = \frac{\rho}{2\pi}\left[\frac{1}{r_1}\right] = \frac{\rho}{2\pi} G_3 \qquad R_4 = \frac{\rho}{2\pi}\left[\frac{1}{r_1 + x}\right] = \frac{\rho}{2\pi} G_4$$

$$R_T = R_1 + R_2 + R_3 + R_4 = \frac{\rho}{2\pi}\left[\frac{2}{r_0}\right] = \frac{\rho}{2\pi} G_T$$

Ground potential rise (GPR) and ground current rise (GCR)

Going back and analyzing the equivalent circuit, the current in the ICT circuit, I_5 due to a GPR can be expressed as:

$$I_5 = I_F \left[\frac{R_2 R_3 - R_1 R_4}{R_T \left(R_S + R_3 + R_4 \right) - \left(R_3 + R_4 \right)^2} \right]$$

Where $R_T = R_1 + R_2 + R_3 + R_4$, and R_S is the sum of the circuit resistance and the resistance between the ground at A and the ground at B.

As previously noted the inductance of the ICT circuit $j\omega L_S$ can be neglected, as it is small compared to R_S.

Ground potential rise (GPR) and ground current rise (GCR)

Then replacing the resistances by ρ/2π times their respective geometric factors in the equation for I_5

$$I_5 = I_F \left[\frac{G_2 G_3 - G_1 G_4}{\left(\frac{2\pi}{\rho}\right) G_T R_S + G_3 + G_4 - (G_3 + G_4)^2} \right]$$

Ground potential rise (GPR) and ground current rise (GCR)

Assuming I_F in the previous slide is described by a double exponential, then $I_5(t)$ is:

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

Where G_{TERM} is the bracket expression from the previous slide

$$G_{TERM} = \left[\frac{G_2 G_3 - G_1 G_4}{\left(\frac{2\pi}{\rho}\right) G_T Z + G_3 + G_4 - (G_3 + G_4)^2}\right]$$

Ground potential rise (GPR) and ground current rise (GCR)

As before, what is of most interest is the energy deposited in R_C. Similar to the previous expression for *J*

$$J = R_C \int_0^\infty i_5(t)^2 dt$$

Then substitution the expression for $I_5(t)$ just calculated into the equation for *J*,

$$J = R_C I_{peak}^2 G_{TERM}^2 \int_0^\infty \left(e^{-2at} - 2e^{-(a+b)t} + e^{-2bt} \right) dt$$

Ground potential rise (GPR) and ground current rise (GCR)

Doing the integration we have:

$$J = R_C I_{peak}^2 G_{TERM}^2 \left[-\frac{e^{-2at}}{2a} + \frac{2e^{-(a+b)t}}{a+b} - \frac{e^{-2bt}}{2b} \right]_0^{\infty}$$

Which evaluates to

$$J = R_C I_{peak}^2 G_{TERM}^2 \left[\frac{1}{2a} + \frac{1}{2b} - \frac{2}{a+b} \right]$$

So now we can put numbers into the equations and make some plots

Ground potential rise (GPR) and ground current rise (GCR)

First of all we need to estimate r_0, the radius of the area rendered conductive by the lightning strike. In the picture below, the literature on lightning shows that the streaks are places where the ground is ionized (and hence conductive). If we assume that the man's feet are a foot apart, then we can estimate r_0 to be 2.4 m (the calculation is not very sensitive to this number).

Ground potential rise (GPR) and ground current rise (GCR)

Some typical numbers to use to make plots for I_5, (noting that r_1 is the distance of the lightning flash from point A) are:

Plot #1

r_1= 30 m, R_s = an X-axis variable equal to R_C plus the 81 ohms previously calculated for the resistance between the ground rods

- or for plot #2 -

r_1 = an X-axis variable and R_S be the sum of 150 ohms (Ethernet with 2 Smith terminations) and the 81 ohm ground resistance.

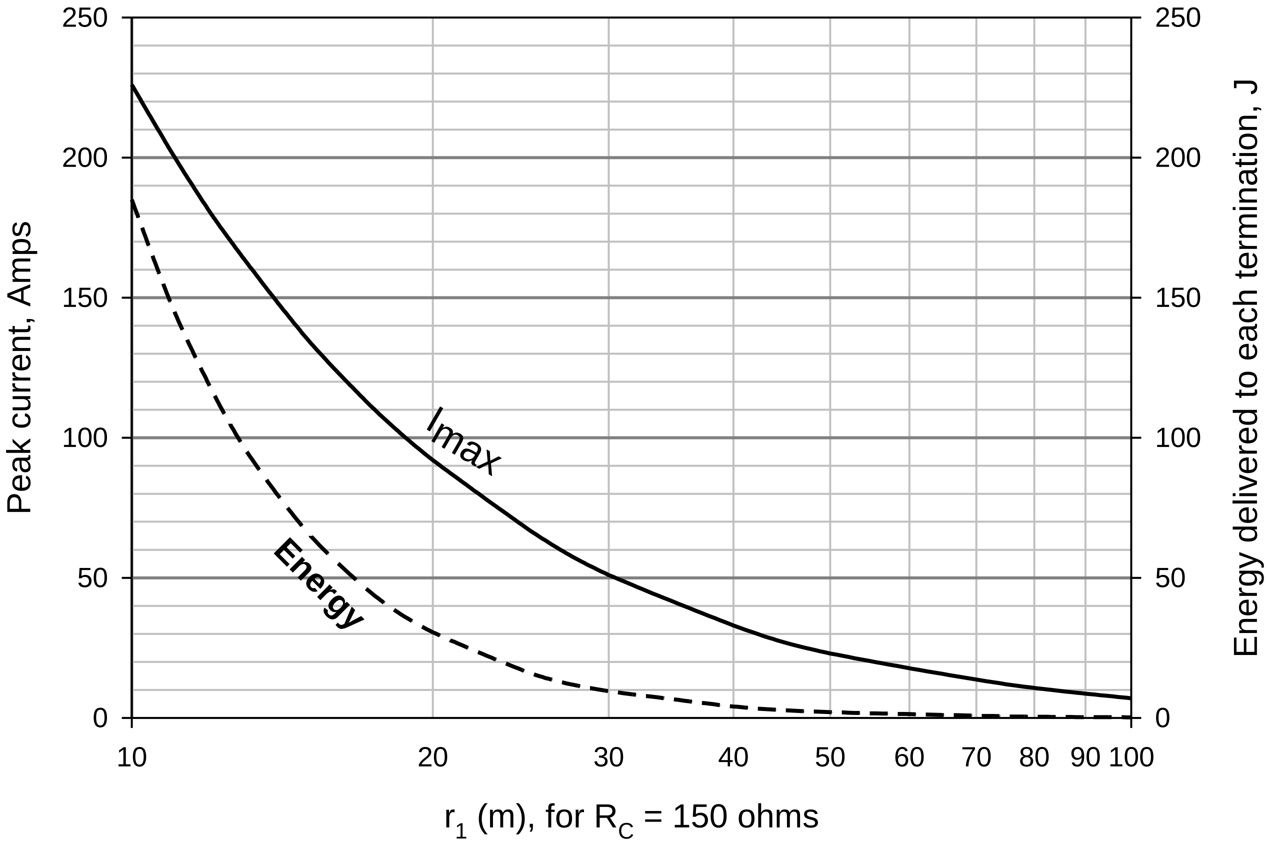
x = 30 m

ρ = 300 ohm-m

These numbers determine the values for G_1, G_2, G_3, G_4 and G_T.

Assume the lightning is a typical 30 kA 5.5/75 strike

Ground potential rise (GPR) and ground current rise (GCR)

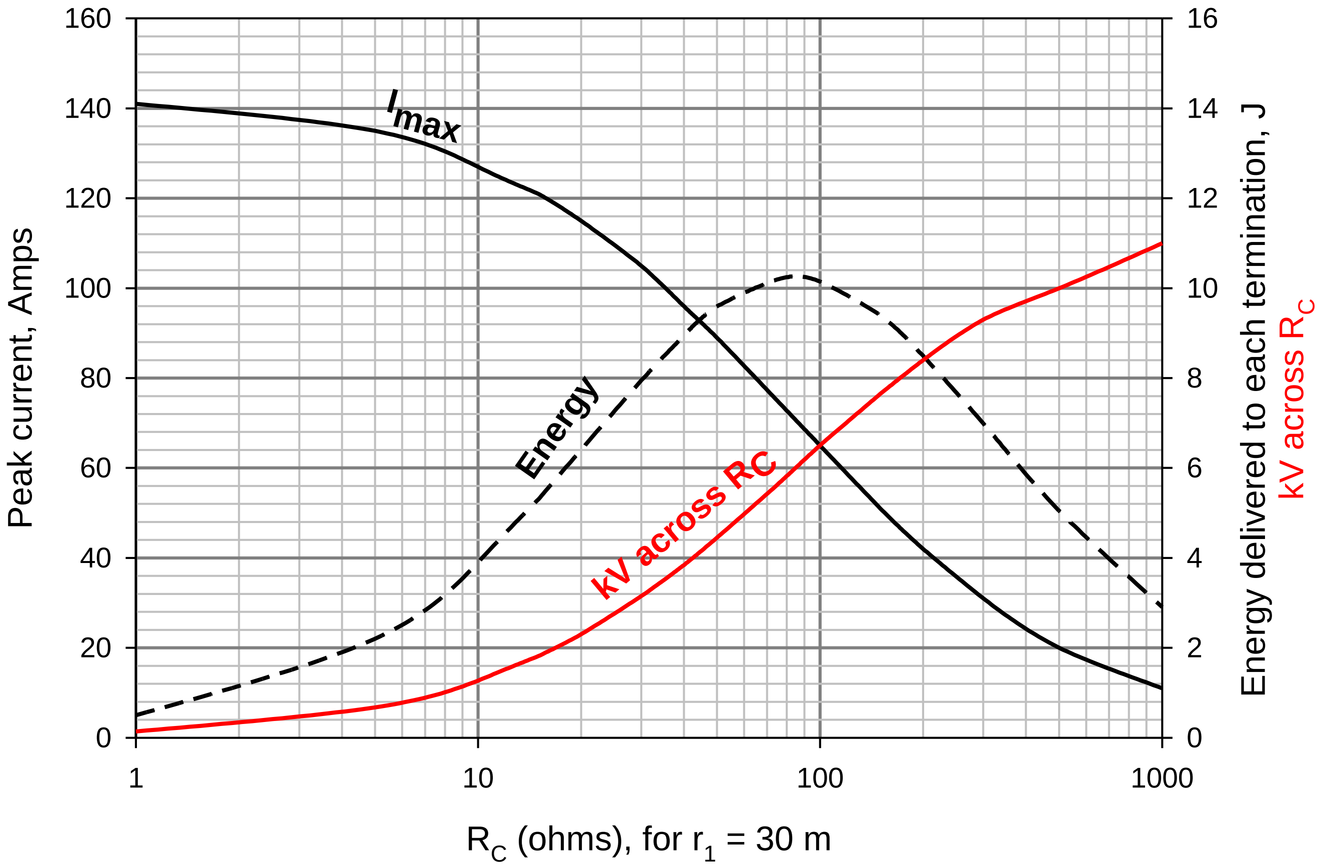


Plot #1

Peak current and Energy delivered to each 75 ohm termination for ground spacing x = 30 m and ground resistance of 81 ohms.

The current and energy are highest when the lightning strike is close by.

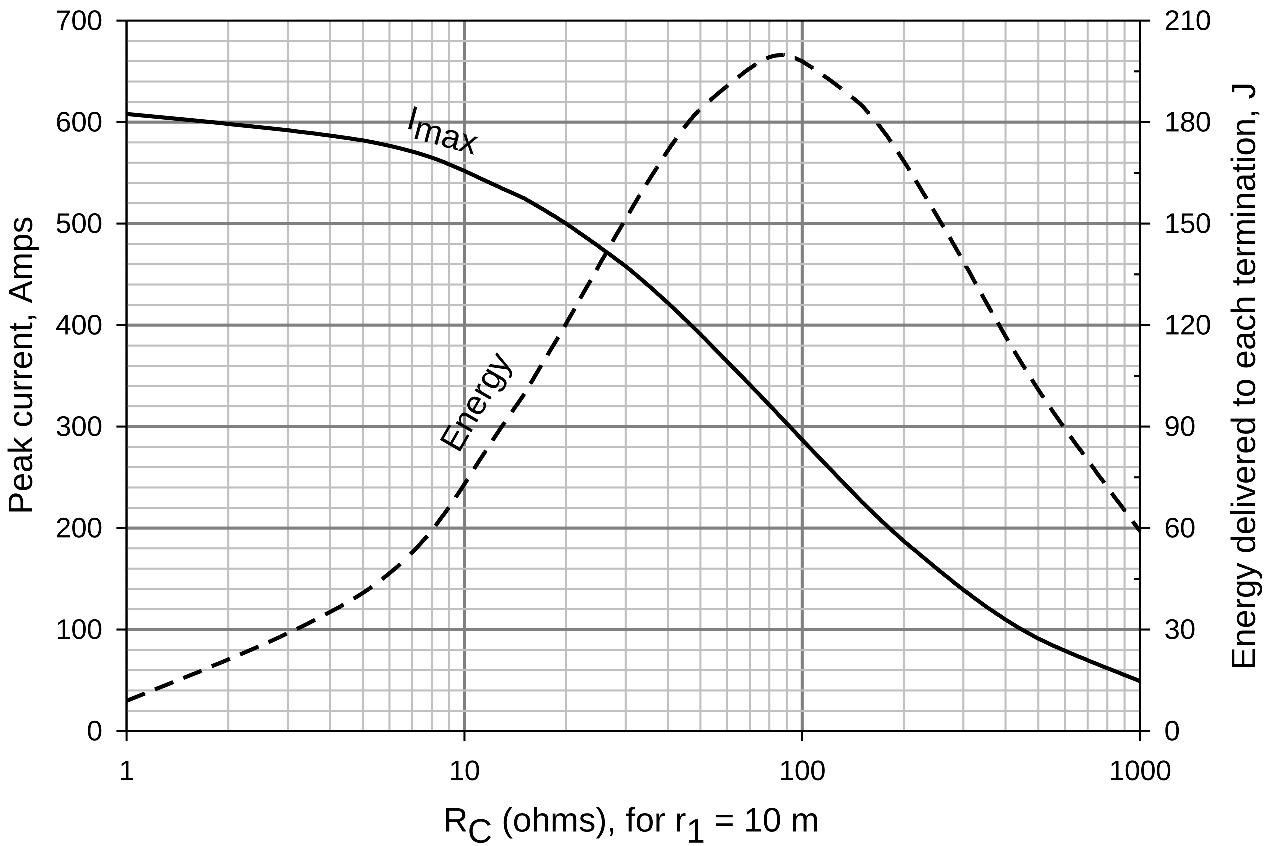
Ground potential rise (GPR) and ground current rise (GCR)



Plot #2

Peak current, energy and voltage delivered to each termination for r_1 = 30 m, ground spacing x = 30 m, and ground resistance = 81 ohms.

Ground potential rise (GPR) and ground current rise (GCR)



This graph shows what can happen if a lightning strike is close to the ICT circuit. It is similar to the previous slide, except that r_1 = 10 m.

Ground potential rise (GPR) and ground current rise (GCR)

As before, assuming an adiabatic process, energy *J* causes the temperature *ΔT* of a device to rise above ambient according to

$$\Delta T = \frac{J}{mc_p}$$

where *m* is the mass of the device in grams and c_p is the heat capacity in Joules/(gram-°C) . For a device made from ceramic or silicon, c_p is 0.85±0.05.

As an example, taking a peak energy of 200 J from the last slide, *ΔT* = 235 °C per gram of device weight. So a small device like a chip resistor could get hot enough to be destroyed.

Ground potential rise (GPR) and ground current rise (GCR)

In addition to energy, voltage across the ICT terminations might be a problem. For example *the voltage that might be developed across a 75 ohm Ethernet termination* for the cases where r_1 = 30 m, r_1 = 10 m and ground resistance = 81 ohms is

3.8 kV for a lightning flash 30 m away

17 kV for a lightning flash 10 m away

Ground potential rise (GPR) and ground current rise (GCR)

The peak currents, energy and voltage in the two cases considered were calculated for a median lightning stroke, and the assumed circuit conditions. They could be more or less than those shown, depending (among other things) on the peak current of the lightning stroke and the length of the ICT circuit.

Also only a single stroke has been considered. Multiple strokes are more common. These can add more energy to the circuit resistances (depending on thermal time-constants), which might lead to a higher temperature rise.

A note on direct strikes

Although it would be a rare event, it's interesting to see what would happen to the loop wire if it were hit by a direct strike.

From [8] for copper wire the specific energy *A* (joules/ohm) to fuse the wire of diameter d in mils is

$$A = I^2 t = 0.024 d^4$$

For a double exponential lightning surge of time-to-half peak = τ,

$$A = 0.72 \tau I_{peak}^2$$ **Substituting this in the previous equation**

$$d = \left(30 I_{peak}^2 \tau\right)^{0.25}$$

A note on direct strikes

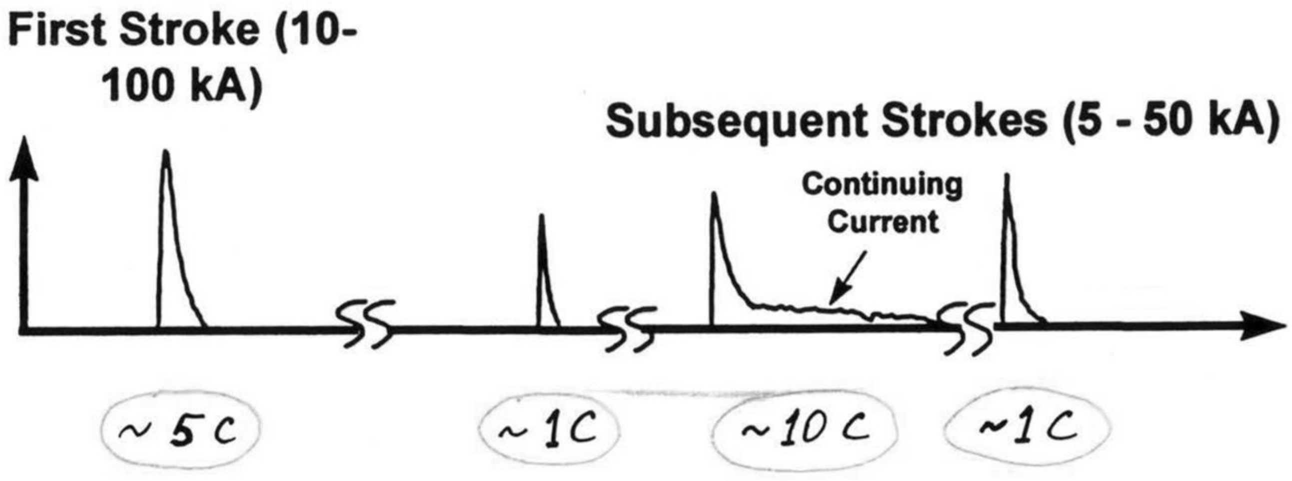
From Wikipedia

$$AWG = 36 - 19.86 \log \frac{d}{5}$$

Any wire with an AWG higher than that calculated from equation above would fuse by the chosen lightning flash. For example for a median 30 kA 5.5/75 stroke, any wire with an AWG equal to or higher than 19 would fuse. A flash with multiple strokes would have higher specific energy, resulting in a lower AWG that for a single stroke.

Multiple strokes and continuing current

Up to this point we have mostly only considered a flash having a single stroke. These are rare. Generally the flash will consist of a first stroke followed by several subsequent strokes and a continuing current, something like that shown below [adapted from Rakov [2]



Multiple strokes and continuing current

Depending on the interval between strokes and the thermal time constant of the device considered, the energy due to the strokes might accumulate in the circuit resistances or the SPD (if there is one). Added to the energy from the strokes is the energy deposited by the continuing currents (if any). In fact the energy due to continuing current might be more of an issue than the energy from the associated strokes. Mick Maytum gave an example of this at the 2014 PEG meeting [3].

Multiple strokes and continuing current

In the case of multiple strokes and continuing current the equations previously developed still apply, but now $i_W(t)$ includes all strokes and any continuing current.

Generally SPDs are not tested for multiple strokes and continuing current, and few standards specify this kind of testing. But there has been some experimental work done, as reported by Yang *et al* [5], Sargent *et al* [6], and more recently by Rousseau *et al* [7].

Multiple strokes and continuing current

Here's example of multiple stroke testing as reported on the *ten350* website. Several tests were run according to the following protocol:

Test number	# Impulses per test	Individual impulse current sizes (in kA) 8/20 μs									
1	3	30	15	30							
2	5	30	15	15	15	30					
3	7	30	15	15	15	15	15	30			
4	10	30	15	15	15	15	15	15	15	15	30
5	3	60	30	60							
6	5	60	30	30	30	60					
7	7	60	30	30	30	30	30	60			
8	10	60	30	30	30	30	30	30	30	30	60
9	3	100	50	100							
10	5	100	50	50	50	100					
11	7	100	50	50	50	50	50	100			

Multiple strokes and continuing current

The surges in the table were spaced 30 ms apart (much shorter than typically allowed by standards). For the most stressful test (test #8) Mick Maytum has shown* that the energy delivered to an SPD could be as much as 10600 J (for a temperature rise of 12,000 ^{0}C/gram!). This is an extreme case, but the energy delivered by a multisurge burst and continuing current can be large.

SPDC web site entitled, "8/20 burst MOV energy"** ***http://pes-spdc.org/content/ten350-web-site?page=1

Multiple strokes and continuing current

There's quite a bit more to say on the topic of multiple strokes and continuing current, but not enough time to go into it here.

For anyone interested current developments on the subject, the IEEE PES SPDC WG3.6.7 has a document in progress which addresses these issues. Other organizations that could be involved are the ITU-T SG5 and the IEC SC37A.

Summary and Observations

Induction effects are likely to be small, mainly because the mutual inductance between the lightning channel and the ICT circuit is small. However flashover could be an issue.

Multiple strokes and continuing current can add considerably to the amount of energy deposited in an ICT circuit, possibly causing destruction, whereas a first stroke alone might not. ***This is an issue with many test standards, which only consider a single stroke (or several strokes, but spaced in time to allow a test device to cool)*****.**

Summary and Observations

Effects of GPR/GCR might be large enough to cause failures, particularly in regard to voltage breakdown, where ICT terminations could be subject to over 10 kV.

A couple of final observations….

Summary and Observations

- The analysis presented here suggests that GPR or GCR can cause failure, something to consider when doing failure analysis.
- When choosing or designing protection, consider that typical lightning flashes have several closely-spaced strokes and often continuing current. These can do a whole lot more damage than either the single-stroke lightning or the multiple-stroke lightning with long times between strokes typically specified in most standards. SPDs chosen without considering this may be damaged or fail to protect.

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So I've run out of blackboard. Any questions?