Power Feeds to Remote Radio Heads…

What protectors need to deal with

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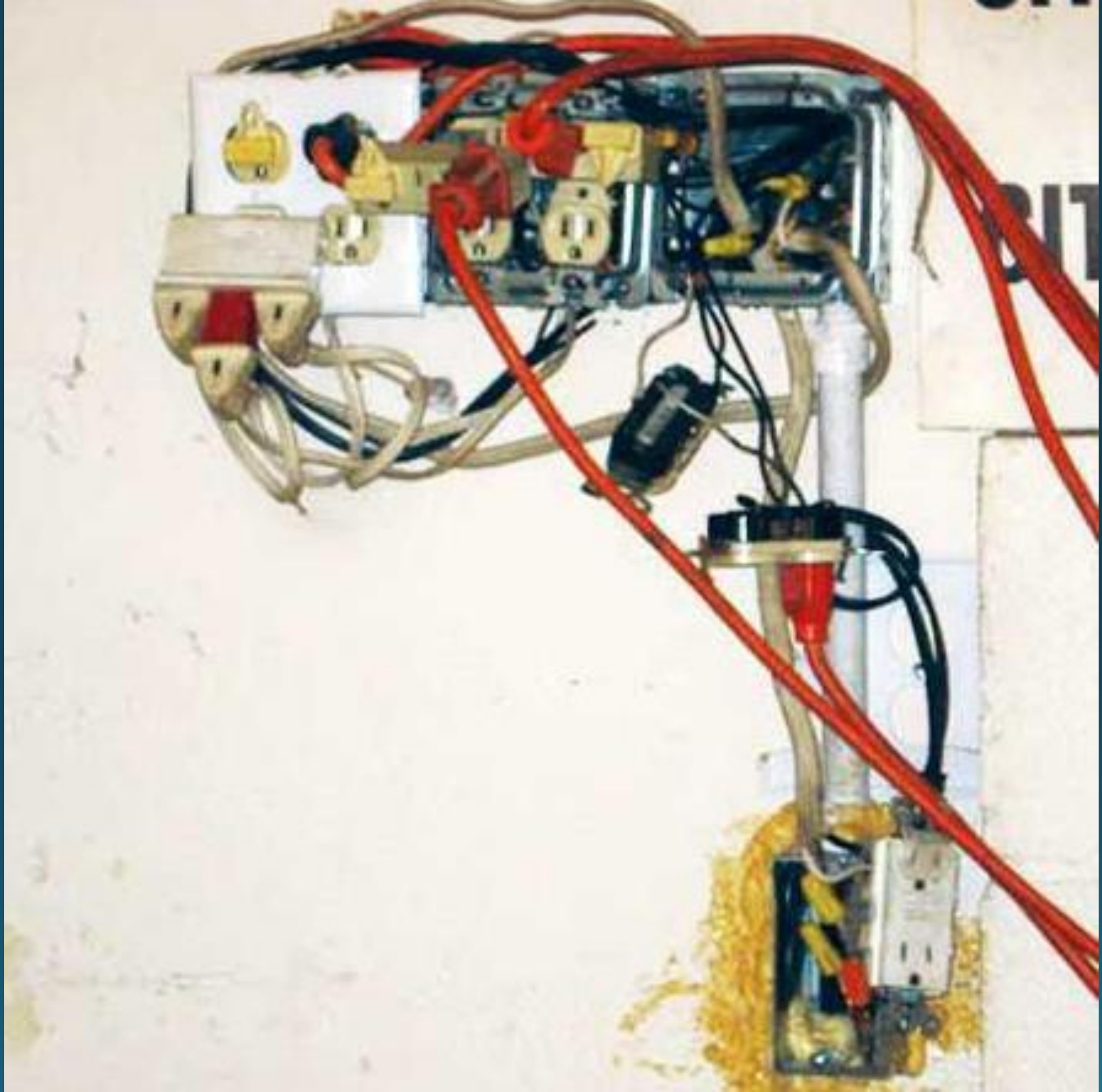

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What protectors need to deal with - agenda

- Lightning types: Lightning is the problem. What are we dealing with?
- Then on to surges on power feeds due to lightning flashes to the tower, illustrated by a relevant use case, and some (surprising) results.
- The consequences of all this for protectors.

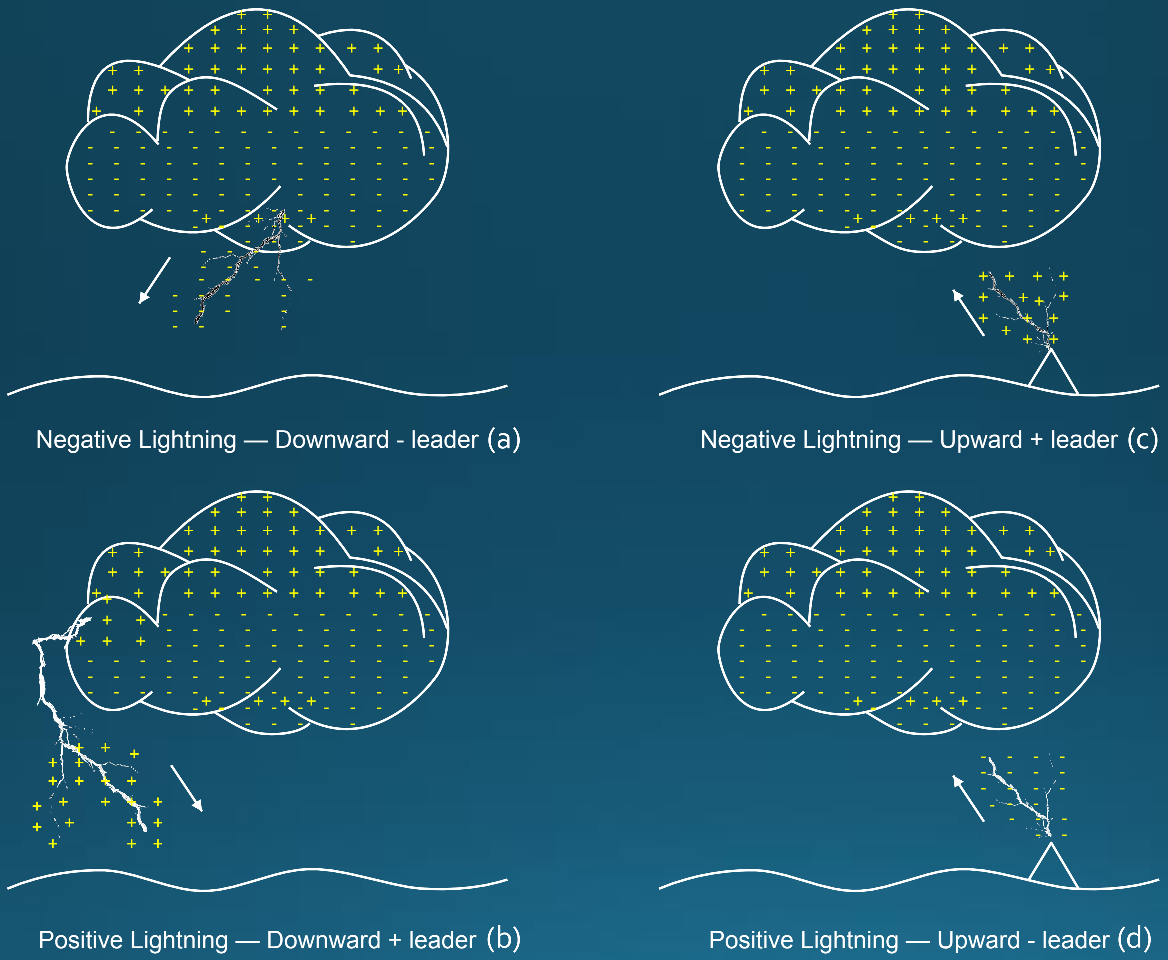
Lightning types

The types of lightning that RRH protectors may need to deal with depend on several things:

- How the flash is initiated
- The polarity of the flash
- The height of any structures involved

So what can we say about these?

Flash initiation - basically 4 types:



Let's see why the type important…

Type (a) Negative Lightning – Downward Leader

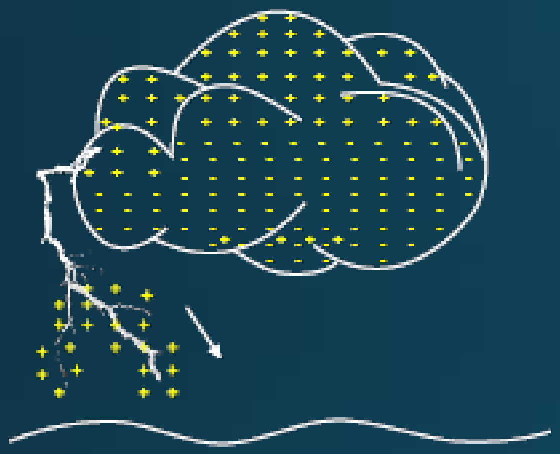
- About 90 % of all lightning is this type
- It characterizes *ground flashes* and flashes to *lower towers*
- It is relatively less severe

Most of the existing data is for this type of lightning; and most equipment will be subject to it (unless the equipment is on a higher tower)

Characteristics of type (a) lightning, (CIGRE TB549 [2])

Parameters	Units	Sample Size	Percent Exceeding Tabulated Value		
			95%	50%	5%
Peak current (minimum 2 kA) First strokes Subsequent strokes	kA	101 135	14 4.6	30 12	80 30
Charge (total charge) First strokes Subsequent strokes Complete flash	C	93 122 94	1.1 0.2 1.3	5.2 1.4 7.5	24 11 40
Impulse charge (excluding continuing current) First strokes Subsequent strokes	C	90 117	1.1 .22	4.5 0.95	20 4
Front duration (2 kA to peak) First strokes Subsequent strokes	μs	89 118	1.8 .22	5.5 1.1	18 4.5
Maximum di/dt First strokes Subsequent strokes	kA/μs	92 122	5.5 12	12 40	32 120
Stroke duration (2 kA to half peak value on the tail) First strokes Subsequent strokes	μs	90 115	30 6.5	75 32	200 140
Action integral ($\int i^2 dt$) First strokes Subsequent strokes	A^2s	91 88	6.0×10^3 5.5×10^2	5.5×10^4 6.0×10^3	5.5×10^5 5.2×10^4
Time interval between strokes	ms	133	7	33	150
Flash duration All flashes Excluding single-stroke flashes	ms	94 39	0.15 31	13 180	1100 900

Type (b) Positive Lightning – Downward Leader



- About 10 % of all lightning is this type
- It also characterizes ground flashes and flashes to lower towers
- It is of medium severity

There is less data for this kind of lightning, but it still needs to be considered, especially for the protection of equipment on low towers.

Characteristics of type (b) lightning

The characteristics of type (b) lightning were discussed in the 2012 PEG meeting [3]. Based on the 2005 data in [4] These are:

Positive first stroke (sample size = 19)

Parameter	Median	Sigma
Peak amplitude (I_p), kA	35	1.21
10 - 90 rise time (T_{10}) µsec	17.6	1.23
Fall time (t_f) µsec	230	1.33

So higher peak current, and much slower rise time and longer fall time than type (a) lightning

Type (c) Negative Lightning – upward Leader

- This type of lightning occurs only to relatively tall towers.
- This type of lightning is infrequent, and the database for it is small, most of it going back to Berger's 1975 paper.
- It is nearly the most severe type of lightning

For tall towers, protection design should be based on the data (however meagre) for this type of lightning

Type (d) Positive Lightning – Upward Leader

- Again this type of lightning occurs only to relatively tall towers
- This type of lightning rarely occurs, but the largest recorded flashes are of this type. It is the most severe.

Characteristics of type (c) and (d) lightning

Because there is so little data on type (c) and (d) lightning, data for both are combined in one table in CIGRE TB549

Parameters	Units	Sample Size	Percent Exceeding Tabulated Value		
			95%	50%	5%
Peak current (minimum 2 kA)	kA	26	4.6	35	250
Charge (total charge)	C	26	20	80	350
Impulse charge (excluding continuing current)	C	25	2.0	16	150
Front duration (2 kA to peak)	µs	19	3.5	22	200
Maximum di/dt	kA/µs	21	0.20	2.4	32
Stroke duration (2 kA to half peak value on the tail)	µs	16	25	230	2000
Action integral ($\int i^2 dt$)	A^2s	26	$2.5x10^4$	$6.5x10^5$	$1.5x10^7$
Flash duration	ms	24	14	85	500

The meaning of “lower” and “tall”

The terms “low towers” and “tall towers” have occurred in previous slides. How do we know which type we have?

A way to look at this is in terms of the type of lightning expected…

The meaning of “lower” and “tall”

Tall towers get hit by the more severe upward flashes, low towers by the less severe downward ones. Which to expect can be calculated as [5]:

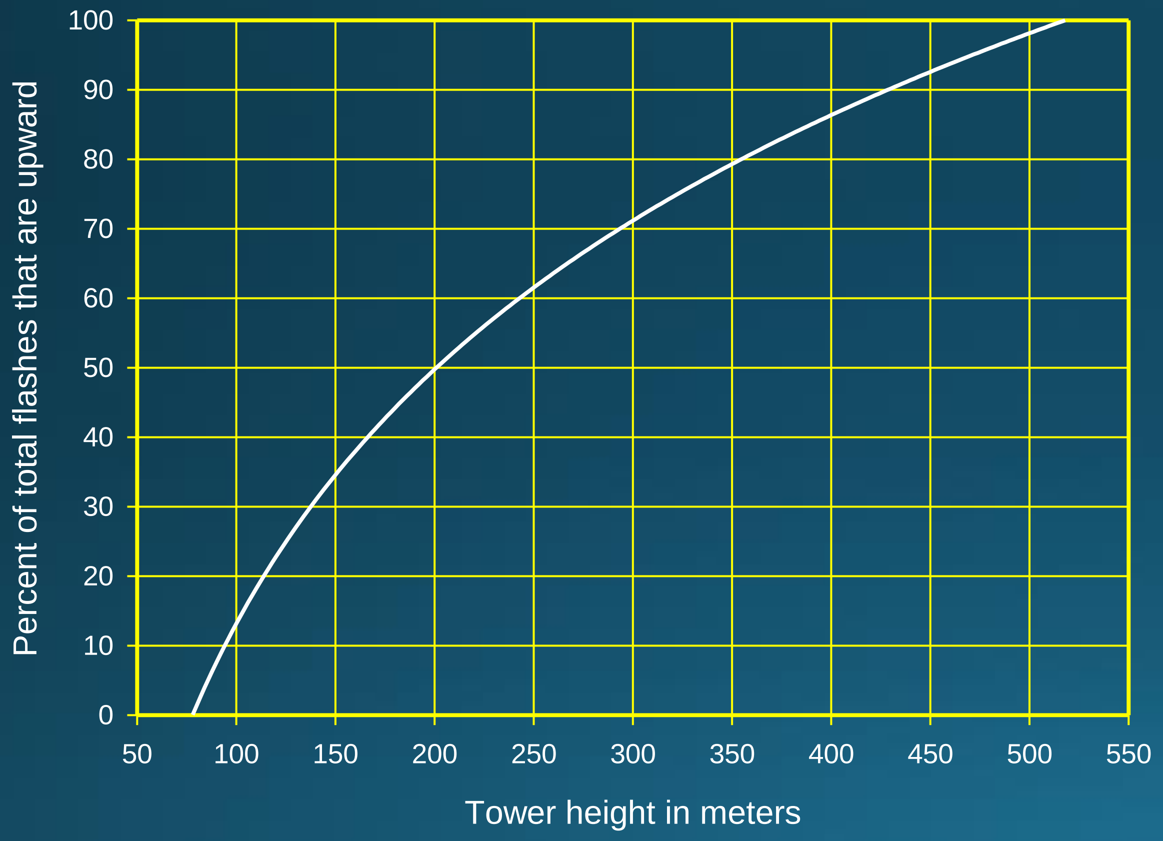
$$P_u = 52.8 \times ln(H_s) - 230$$

where P_u is the percentage of upward flashes and H_s is the structure height in meters.

Structures with Hs ≤ 78 m (250 ft) are expected to be struck by downward flashes only (P_u = 0), and structures with Hs ≥ 518 m (1700 ft – there are some) are expected to experience upward flashes only (Pu = 100). What about in between?

Flash type vs. height

This plot of the equation on the previous slide may help decide.



Tall towers have a higher percentage of the more severe positive flashes. So for tall towers the table of values for upward flashes would be chosen. Lower towers would use the tables for downward flashes

Evolution of the problem

Historically tower top installations (usually antennas) were fed by coax from equipment at the base of the tower.

Evolution of the problem

Now principally to reduce transmission losses, active radio equipment is placed at the top of the tower next to the antenna. Fiber optic cables carrying the signal to be broadcast are run up to the equipment where the light signals are converted into RF power to drive the antennas.

The equipment is typically powered by a low voltage power line (typically 48 V DC) run up to the equipment from a power supply at the base of the tower.

The issue

Towers regardless of height are likely to be struck by lightning, which will cause a surge on the RRH power feed. Because of that, surge protection is needed.

What will this protection have to deal with?

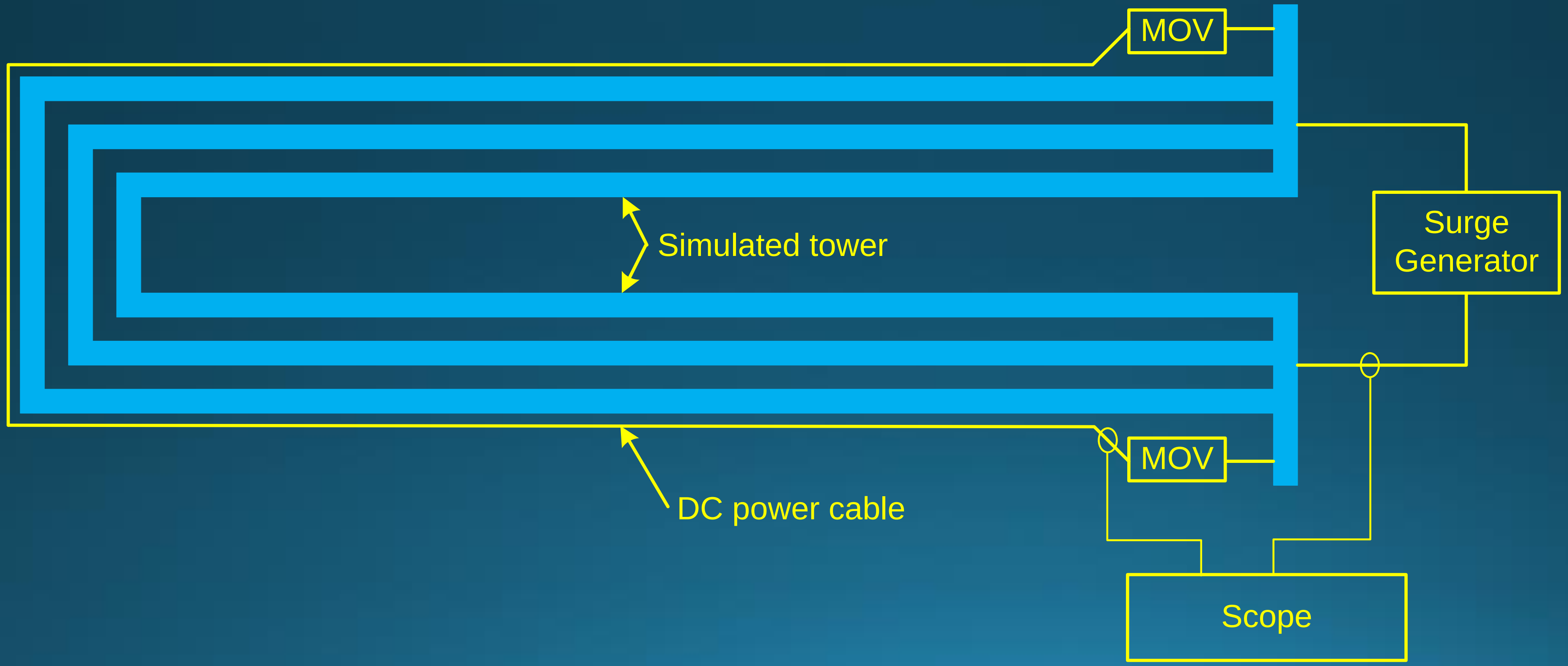
The issue

To see what protectors need to deal with it is useful to look at a use case.

There are a couple, and the details of these can be found in [8] and [9].

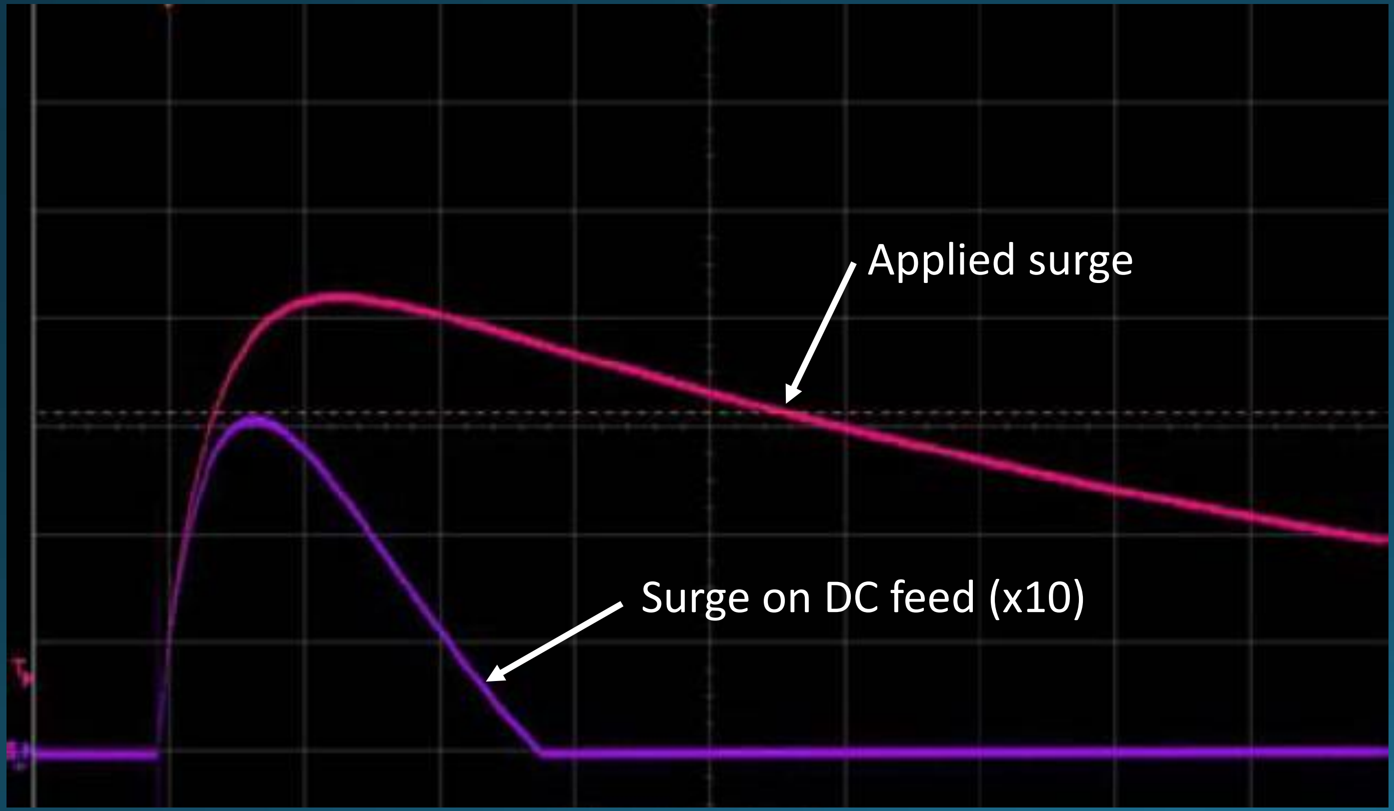
The use cases

In both cases a simulated tower and MOV protection was set up in a lab, for example like this (adapted from [9]), Where a simulated tower of square steel tubes was bent in a U shape to minimize the generator leads, and the feed wire was protected with MOVs at each end



The use cases

When the surge was applied the result was like this (adapted from [9]):



Hmmm… Well what would generally be expected is that the waveshape of the current on the power feed would match that of the applied surge – *clearly not the case!*

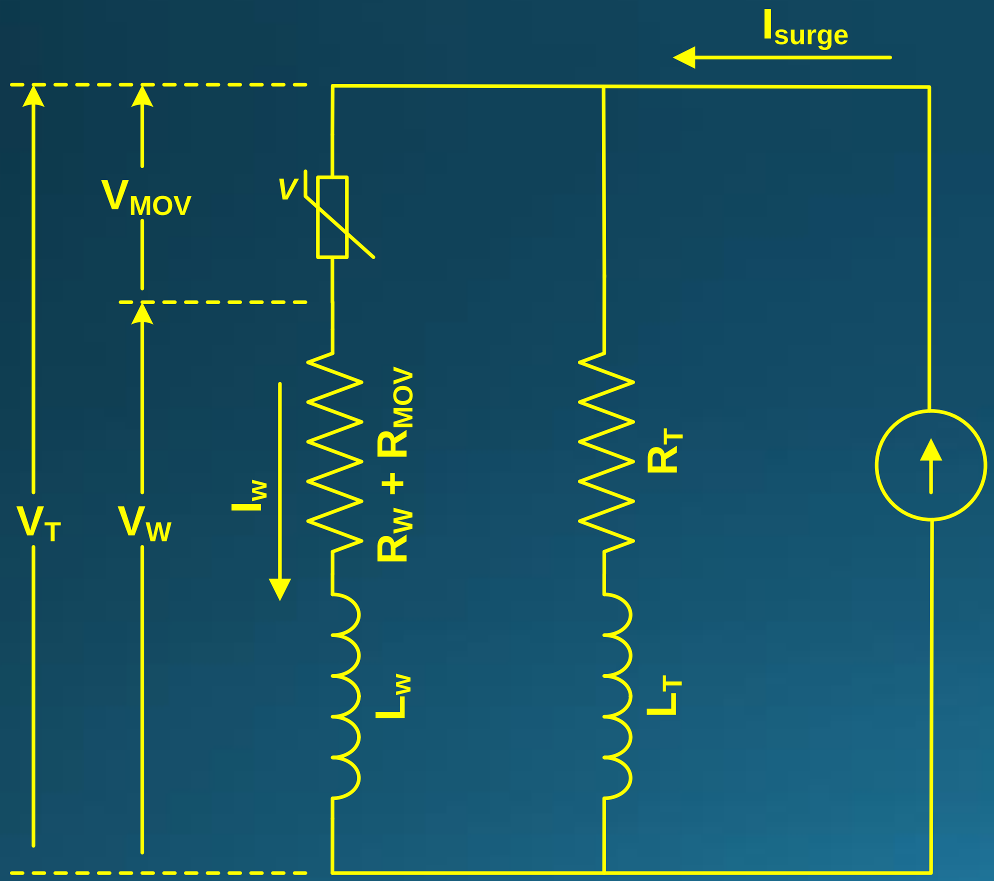
So what's going on?

The solution

One way to see what's happening is to create a model for the use case tower and the power feed, and then see if the predictions of the model match the results of the use case. If they do, then we can be reasonably confident that we know what's going on.

The solution

For the model we can use an equivalent circuit for the tower and power feed:



R_w and L_w are the resistance and inductance of the wire

R_T and L_T are the resistance and inductance of the tower

R_{MOV} is the resistance of the 2 MOVs, and V_{mov} is the sum of the voltages across the 2 MOVs

The solution

The equivalent circuit can be used to calculate the waveform on the power feed. Then to validate the analysis, the calculated waveform needs to be compared to an actual measurement.

Fortunately in the use case developed in [9] we have an actual measured waveform. So for the validation, we can compare this to the wire waveform calculated for the equivalent circuit.

The solution

From an analysis of the equivalent circuit, here is an expression for the current in the wire:

$$I_W = \left[\mathrm{k}I_f(s)\,\frac{L_T}{L_S}\right]\left[\frac{s+d}{s+c}\right] + \frac{V_{MOV}}{L_S}\left[\frac{1}{s(s+c)}\right] \qquad (1)$$

Where

I_W = current in wire, I_f = flash current

$c = \frac{R_S}{L_S}$, $d = \frac{R_T}{L_T}$, $R_S = R_W + R_{MOV} + R_T$, $L_S = L_W + L_T$, s = jω

Let h = height of tower

R_w = h*(ohms per meter of wire

L_W = h*(inductance per meter of wire)

R_T = h* (ohms per meter of tower

L_T = h*(inductance per meter of tower)

The solution

The coupling factor k to use in equation (1) is discussed in detail in

ITU-T k.97, and is given by k = $\alpha_F\alpha_T$, where α_F is the coupling effect of the cable tray, and α_T is the coupling effect of the tower. Essentially these correct for variables not accounted for in the calculation.

In the present case there is no cable tray, so $\alpha_F = 1$.

From ITU-T K.97, α_T ranges from 0.1 to 0.3. In the present case we can determine α_T as 0.25 from the ratio of measured to unadjusted calculated peak current in the power feed, which is within the ITU-T K.97 range of values.

The solution

Now assume that I_f (t) is in the form of a double exponential:

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

$$I_f(s) = \frac{\mathrm{k}I_{peak}(b-a)}{(s-a)(s-b)}$$

Where I_{peak} = peak of the flash current. From equation (1)

$$I_W = I_f(s)\,\frac{L_T}{L_S}\left[\frac{s+d}{s+c}\right] + \frac{V_{MOV}}{L_S}\left[\frac{1}{s(s+c)}\right]$$

$$I_W(s) = \mathrm{k}I_{peak}\left(\frac{L_T}{L_S}\right)\left[\frac{(b-a)(s+d)}{(s-a)(s-b)(s+c)}\right] + \frac{V_{MOV}}{L_S}\left[\frac{1}{s(s+c)}\right] \qquad (2)$$

The solution

The LaPlace transform of (2) gives the circuit response in the time domain:

$$I_W(t) = \mathbf{k}I_{peak}\frac{L_T}{L_S}\left[\frac{d-a}{c-a}e^{-at} - \frac{d-b}{c-b}e^{-bt} + \frac{(b-a)(d-c)}{(c-a)(c-b)}e^{-ct}\right] + \frac{V_{MOV}}{cL_S}\left[1-e^{-ct}\right]$$

Substituting values for a, b, c, d, k and I_{peak} into this equation gives the waveform of $I_W(t)$

The solution

From the use case [9] plus calculated resistance and inductance for the wire, and resistance and inductance values calculated by Mick Maytum for a 3-leg tower [10] and :

Lightning surge = 42.5 kA

Wire resistance R_W (ohms) = 0.068

Wire inductance[1] L_S (μHy) = 18

Tower resistance R_T (ohms) = 0.0022

Tower inductance L_T (μHy) = 5.8

MOV clamp V = 100 (each one, 200 V total)

Waveshape = 56.5/431, for which a = 1920 and b = 68600

$$c = \frac{R_S}{L_S}, \quad d = \frac{R_T}{L_T}, \quad R_S = R_W + R_{MOV} + R_T, \quad L_S = L_W + L_T$$

[1] Wire inductance is important but difficult to calculate, since it is significantly influenced by the spacing and shape of neighboring conductors, and the presence of magnetic material.

The solution

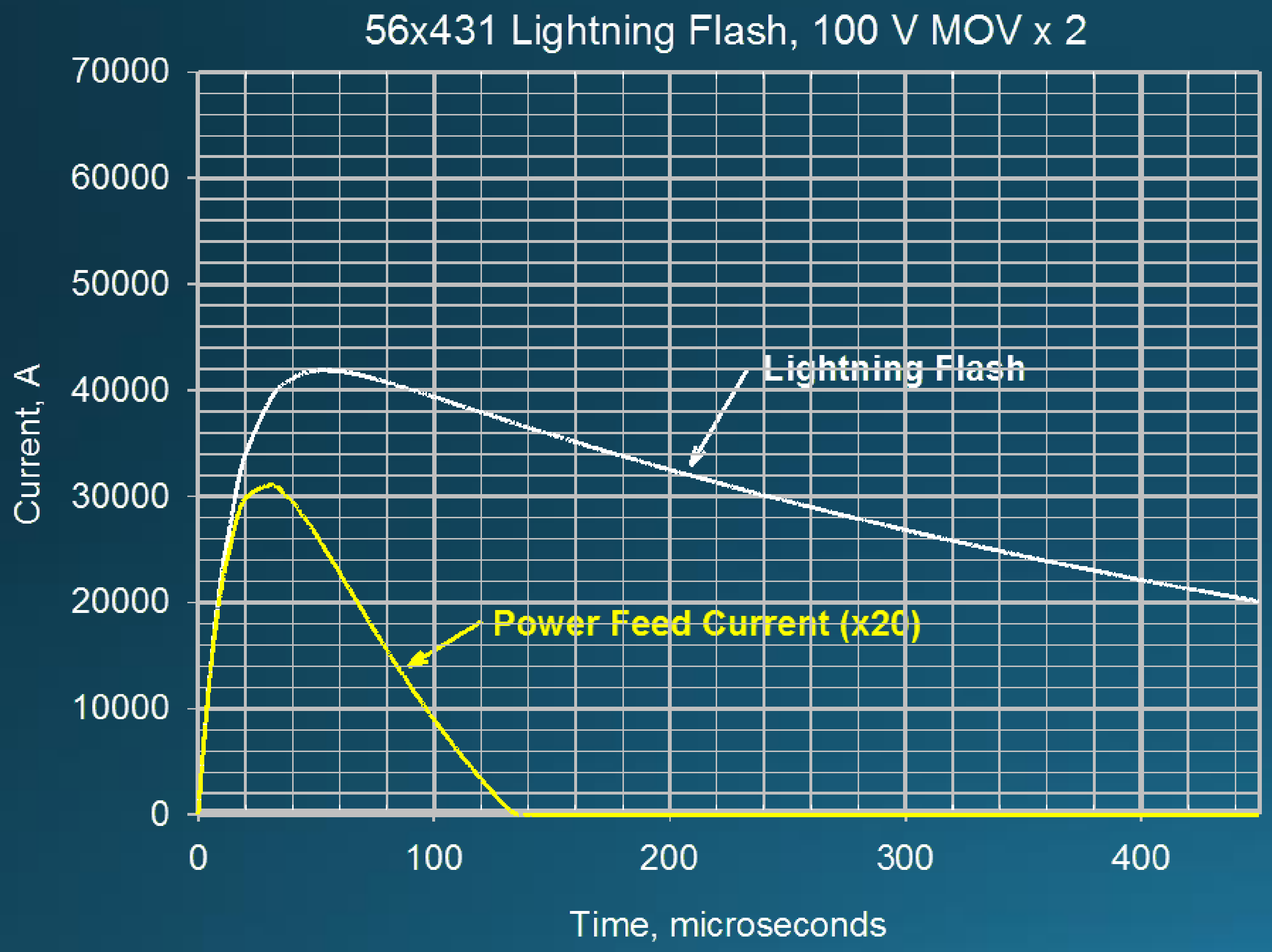
The resistance of the MOV, R_{MOV}, depends on the current flowing through it, and changes as the current changes. It is difficult to take the instantaneous value of R_{MOV} into account. As an approximation its average value can be calculated from

$$R_{MOV} = \frac{V_{MOV}}{I_{ave}} = \frac{V_{MOV}}{\frac{1}{T_{max}} \int_0^{T_{max}} i(t)dt} = \frac{T_{max} V_{MOV}^2}{W}$$

Where W is the energy dissipated in the MOV (see later slide), and T_{max} is the time at which I_W goes to zero.

In the present case (2 MOVs in series), R_{MOV} = 0.12 ohms

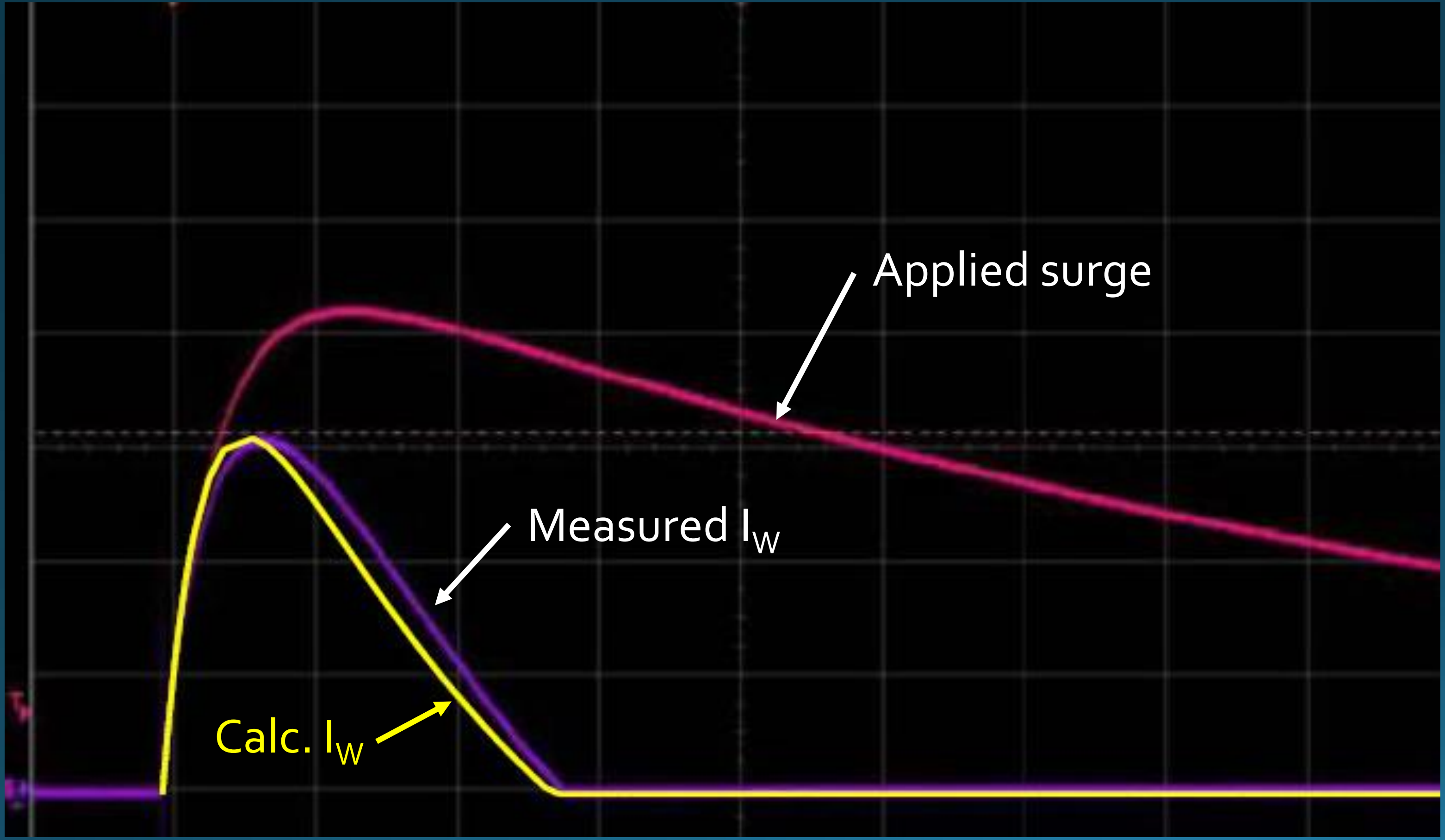
The solution



Using the values from the previous slide in the equation for $I_W(t)$, here is a plot of the calculated wire current (shown x20). Note that in this case the duration of the wire current is much less than the duration of the flash (first noted by Mick Maytum in 2012 [11])

The solution

Here is the plot from the use case [9] with the calculated current in the power feed, I_W, superimposed



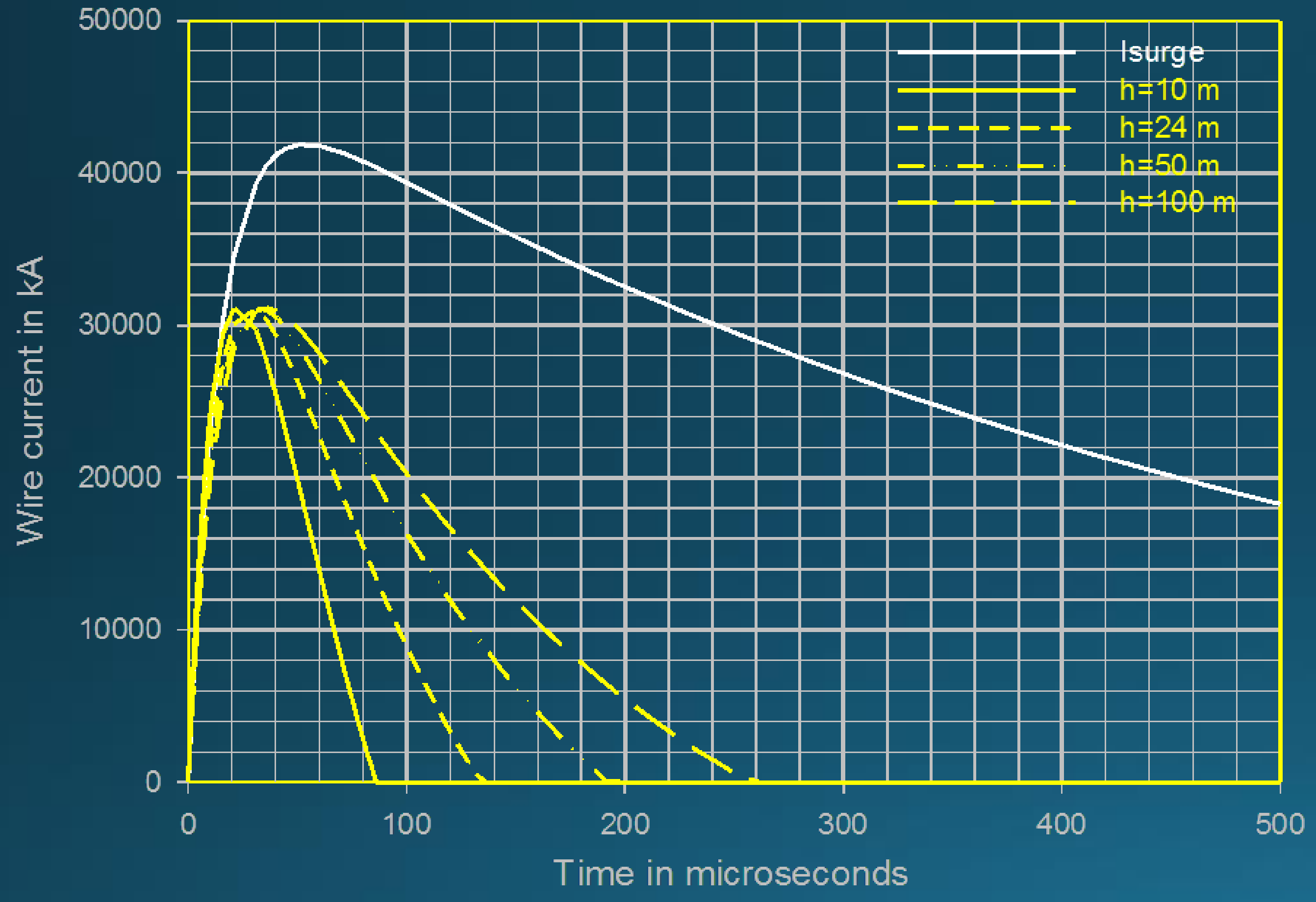
Comparing the measured and calculated waveforms , the overall the correlation is good, considering that the calculation uses values derived from an analysis of the structure used in the experimen

The solution

The correlation between measured and calculated waveforms is quite good. So it's reasonable to conclude that the increase of the resistance of the MOV (and by extension, any clamping device) when the voltage across it falls below the clamping voltage is responsible for the waveform of the current in the power feed.

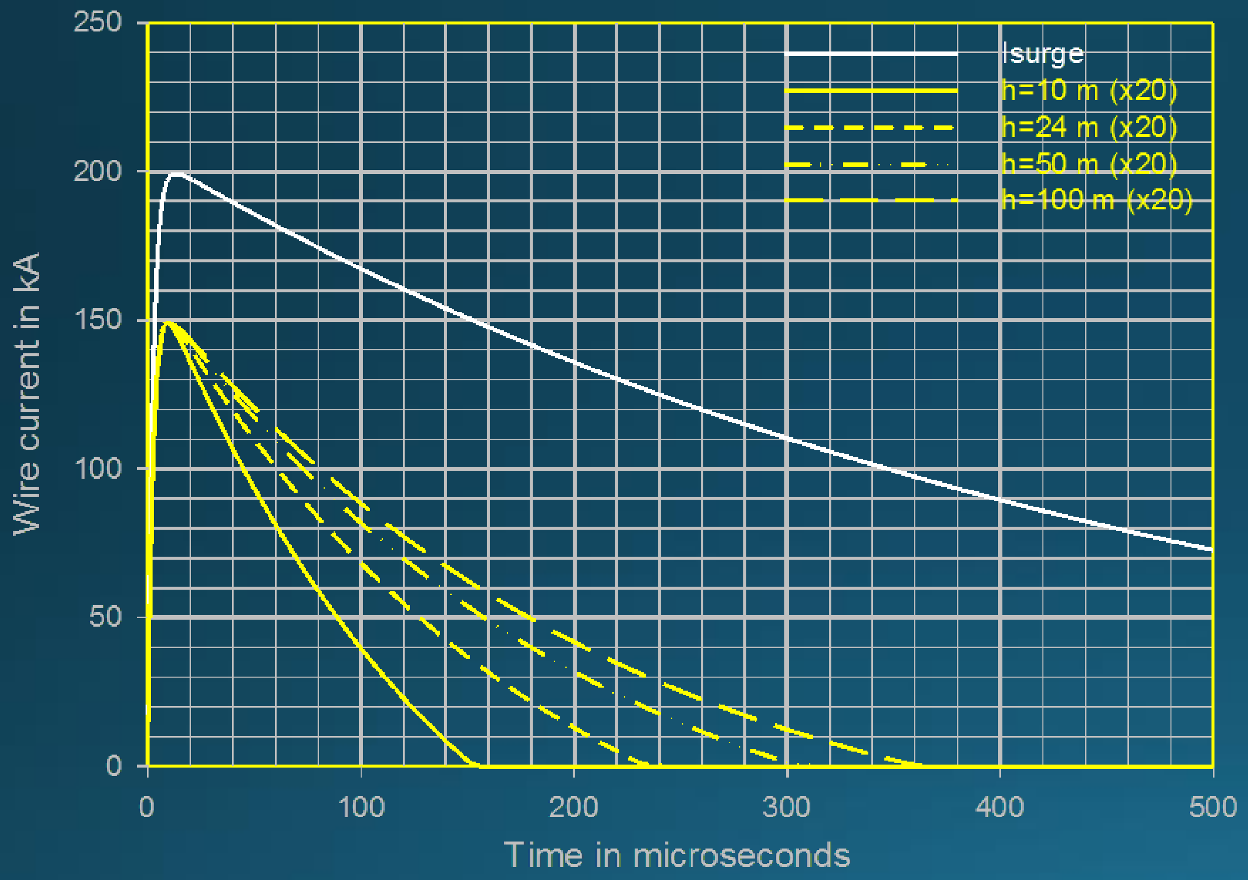
So if the power feed protection is a MOV, its affect on waveform needs to be considered.

Examples of how the model can be used



Assuming the power feed protection is a MOV, let's see what happens to I_W, if we go back to the use case and vary the height of the tower, holding all else constant. As h goes from 10 m to 100 m, T_0 goes from 86 to 258 µs. So tower height influences the waveshape of I_W.

Examples of how the model can be used



Let's look at the mother of all surges – the 200 kA 10/350. Again this example uses the resistance and inductance values of the use case, with only the height as a variable. Note that the I_W waveshapes don't look anything like a 10/350. They range from 9.2/66 to 9.6/124, and the peak amplitudes are much less (shown x20 on the graph)

Examples of how the model can be used

As a note, studying the effect of changes in variables shows that the waveform of the surge on the power feed is most affected by the waveform of the flash to the tower and the inductance of the wire.

Protector using a clamping device

For protector design, the consequence of using a clamping protector on the power feed is that the amount of energy delivered to the device is the most important parameter, since the device can fail due to overheating. This energy *W* is given by:

$$W = V_{MOV} \int_0^{T_{max}} i_W(t)dt$$

Where T_{max} is the time the wire current falls to zero, and $i_W(t)$ is the time-domain wire current shown earlier.

Protector using a clamping device

To calculate W, a reasonable choice for the lightning flash waveform to be used in the calculation of $I_W(t)$ can be found in the tables shown earlier for the various lightning types, and will typically be the value for a 5% probability of occurrence, for a margin of safety in the protector design. The table to use depends on the combination of tower height and the acceptable risk of occurrence of the lightning flash, as previously discussed.

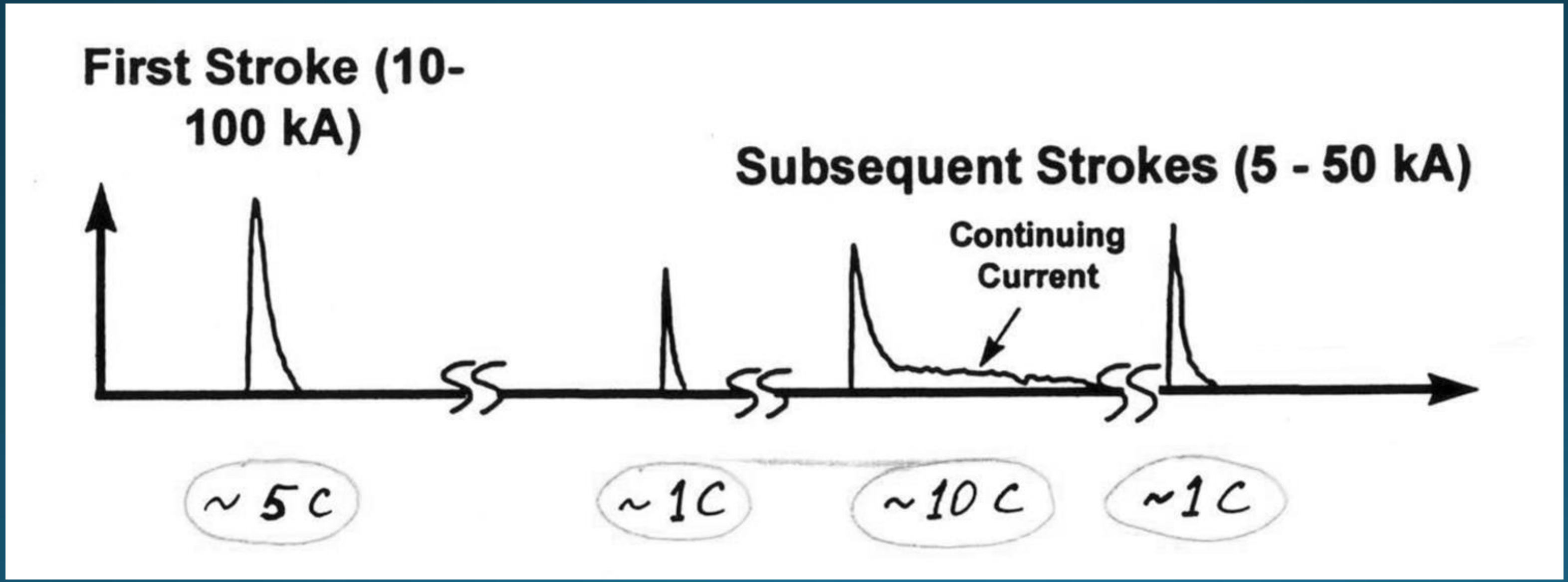
Once the variables for the expression for $i_W(t)$ have been determined, the energy in the clamping device can be calculated as shown on the previous slide.

In the use case example each MOV has to handle W = 23 Joules.

Protector using a clamping device

Additional considerations

Up to this point we have considered a flash having only 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 this (adapted from [12]):



Protector using a clamping device

Depending on the interval between surges and the thermal time constant of the clamping device, the temperature of the clamping device can increase due to the accumulated heat energy. If the temperature rise is high enough, the device can be destroyed.

For example, the use case from Mick Maytum's presentation at the 2014 PEG meeting [13]:

Q: Why did a 40 kA SPD fail at lightning currents no greater than 1.6 kA?

A: Appears to be the cumulative energy delivered by the 350 A, 0.5/29.5 first stroke followed by eight return strokes ranging from 0.22 kA to 1.64 kA with a geometric mean waveshape of 15.6/63.3, plus several impulses which show a continuing current content lasting some 3 ms and delivering 100 J.

Protector using a clamping device

So with a clamping device, the important thing to consider is the amount of *energy* deposited in the device by all components of the flash: First stroke, subsequent strokes, and continuing current.

A protector chosen without consideration of energy may be undersized, as the example just cited shows.

What protectors need to deal with…

So what can we say about all this?

First we need to consider the lightning flash

As we discussed in the beginning, the character of a lightning flash depends on how the flash is initiated and the polarity of the flash.

There are 4 possible combinations of these, and a table corresponding to each case was given. The table to use depends on the height of the structure involved. A relation between the tower height and the probability of occurrence of the flash type was given, as a pointer to the table to consider.

What protectors need to deal with…

Then we need to consider the protector itself

The most common protector on an RRH power feed is a clamping device. In this case as the voltage across the device falls below its clamping voltage, the resistance of the device goes up, causing a diversion of the flash current to other conductors in the area.

The result of this action is that the surge in the power feed is decreased in amplitude and shortened relative to the duration of the lightning flash. How much shorter, and how much smaller the amplitude, depends on the variables listed earlier.

What protectors need to deal with…

Finally we need to consider protector survivability

What we're really interested in is the ability of the protector to survive. In the case of a clamping protector, the key to the survivability is the total energy deposited in the protector by the surge on the feed wire, since that energy is responsible for heating the device, possibly to the point of failure.

So that's it…

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

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

[4] Lightning and Insulator Subcommittee of the T&D Committee (2005), "Parameters of Lightning Strokes: A Review". *IEEE Trans. On Power Delivery, Vol 20, No. 1, pp 346 - 358.*

[5] Eriksson, A. J. (1987), The Incidence of Lightning Strikes to Power Lines, Power Delivery, IEEETransactions on Transmission and Distribution , vol.2, no.3, pp.859-870.

[6] Gamerota, W. R., J. O. Elismé, M. A. Uman, and V. A. Rakov (2012), "Current Waveforms for Lightning Simulation", IEEE Trans. on Electromagnetic Compatibility, Vol. 54, NO. 4, pp 880 – 888.

[7] Berger, K., R.B. Anderson, and H. Kroninger (1975). Parameters of Lightning Flashes. Electra vol 41, pp 23-37.

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[8] Xiong, Y. (2013). "Lightning current waveform on DC power conductor along tower", ITU-T document *TD 94rev1*, Geneva, January 2013.

[9] Zafiris, Politis, "Lightning current through MOV based SPDs in RRH applications", Raycap GmbH, Parkring 11, 85748 Garching bei München, Germany.

[10] Matum, M.j. (2014), "Remote Radio Unit (RRU) DC Feed protection", working document contributed to IEEE PES SPDC WG3.6.3.

[11] Maytum, M.J. (2012), " Towering Powering protection problem on Remote Radio Head (RRH) cellular systems", The Alliance for Telecommunications Industry Solutions Protection Engineer Group Conference, March 13 - 15, 2012, Huntsville, Alabama.

[12] Rakov, V. A. (2012), "Lightning parameters of engineering interest: Application of lightning detection technologies", EGAT, Bangkok, Thailand, November 7, 2012.

[13] Maytum, M.J. (2014), "Technical Bulletin (TB) 549 (2013) Lightning Parameters for Engineering Applications", The Alliance for Telecommunications Industry Solutions Protection Engineer Group Conference, March 25 - 27, 2014, Littleton, Colorado

Questions?