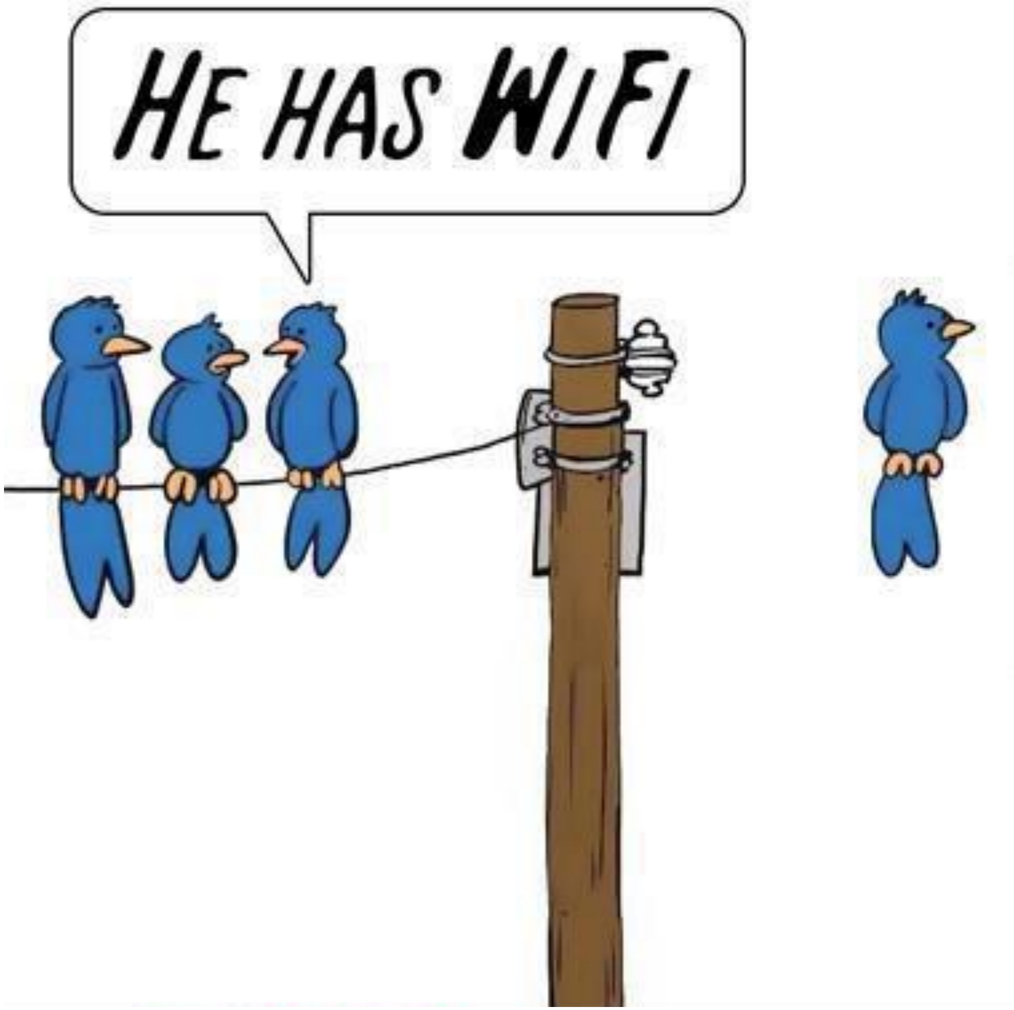

HE HAS WIFI

Effect of multiple lightning surges on SPDs using MOVs

PEG CONFERENCE

Presented by:
Al Martin
GGG

The story begins with Karl Berger. Karl Berger was a professor of high voltage engineering at ETH Zurich. He was known as the “father of lightning research” for his pioneering observations at the lightning-detection station on Monte San Salvatore from 1943 to 1972 . Ever since his work during this time, a lightning flash has been known to consist of a burst of a first stroke followed by several subsequent strokes, all spaced a few milliseconds apart. This structure was clearly shown in his 1967 paper [1].

Since Karl's time a few test labs have constructed equipment to do multiburst testing (Darveniza and co-workers in Australia, Ray Hill and co-workers at Georgia Tech, and recently Zhang and his co-workers in China)

Since the structure of a lightning flash has been known for a long time, and we know it can be done, why hasn't multiburst testing simulating lightning made it into test standards?

One possible reason goes back to the observation by Bodle et al in 1976 [2] that, *"For design tests of the lightning withstand capability of plant items and associated equipment, both in the communication and power industries, a single large impulse is employed. This is an 'equivalency' type of test dictated by practical test considerations. Experience has indicated, however, that this is an acceptable simulation of actual field exposure, which includes multiple component strokes*."

So what Bodle and his co-authors are saying is that Yeah, we know about multiple component flashes, but multiple-surge testing isn't needed because single large-burst testing works well enough (which was probably true in 1976 when they were writing).

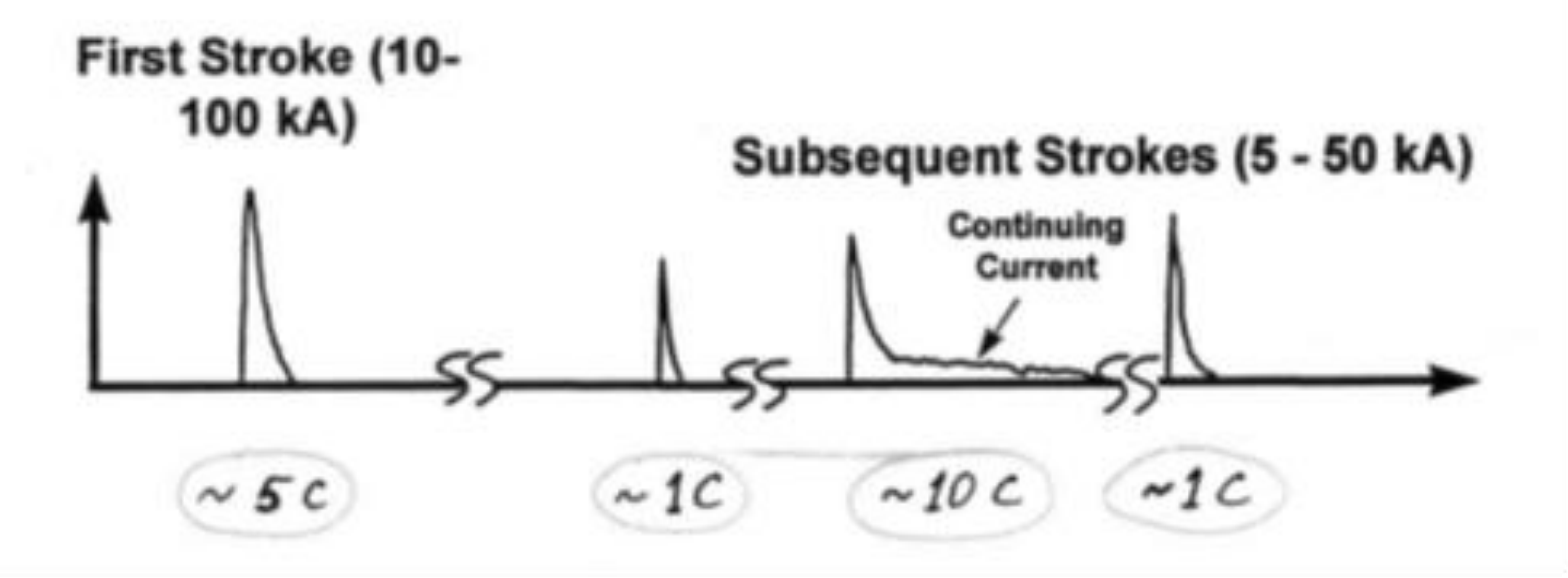
A second possible reason is that equipment to do multiburst testing is not commercially available, and would likely be expensive if it were.

Either way multiburst testing is generally not done on protectors used on ICT systems and, if present, associated dc power.

So what do we miss by testing with a single large surge or multiple surges widely spaced?

If we're testing switching SPDs, then there may not be a problem, But there could be with clamping SPDs because clamping SPDs, especially MOVs, can have a potentially destructive temperature rise caused by heat accumulation in the SPD from a multisurge burst, and in some applications, continuing current. That's potentially what we miss when a multisurge burst test is replaced by a single large surge, or multiple surges spaced widely apart.

Here's an example of a lightning flash where we might expect heat accumulation to occur[1]



[1] after Rakov, [10]

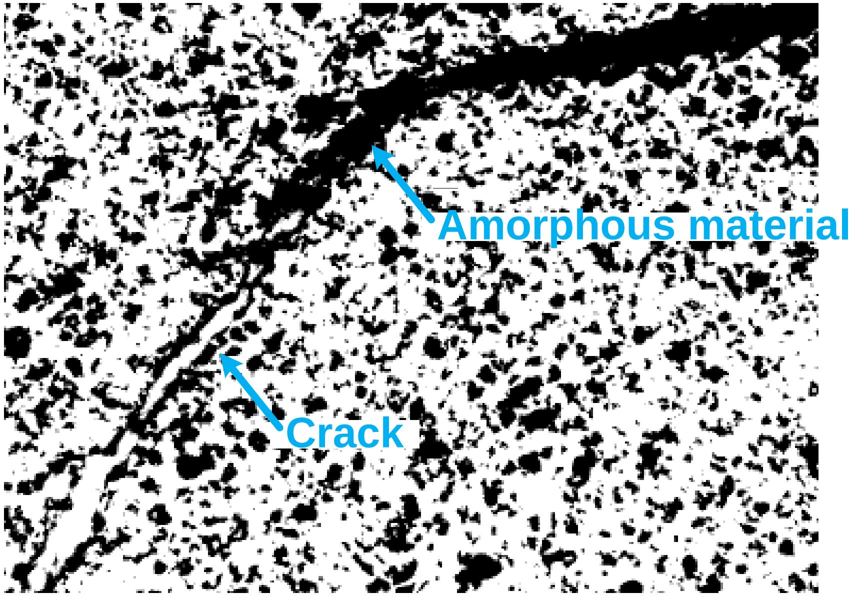
The view that multisurge burst testing is needed is supported by several studies including those by Darveniza and his co-workers, specifically Sargent *et al* [3], and that of Rousseau *et al* [4]. All these studies found that MOV samples subjected to multiple surges failed when the surges were closely spaced, *but not when the samples were allowed to cool in between surges*.

Heat accumulation is particularly relevant to MOVs, because MOVs have a long thermal time constant. As the cited studies show, due to the long thermal time constant, the energy deposited in a MOV from one of a series of closely-spaced surges might not dissipate before the next surge arrives, allowing energy to build up. The same is true for silicon-based devices, but to a lesser extent, because the thermal time constants for silicon devices are shorter than for MOVs.

Since the heating effect is largest in MOV's, we'll concentrate on them; and in a particular returning to a specific application of MOVs, the protection of DC feeds to remote radio heads, a topic discussed at the 2015 PEG meeting [5].

Thermal modelling of MOVs

In the study of Sargent *et al*, analysis of the failed MOV samples showed the existence of a conduction channel having cracking and the adjacent formation of new amorphous material

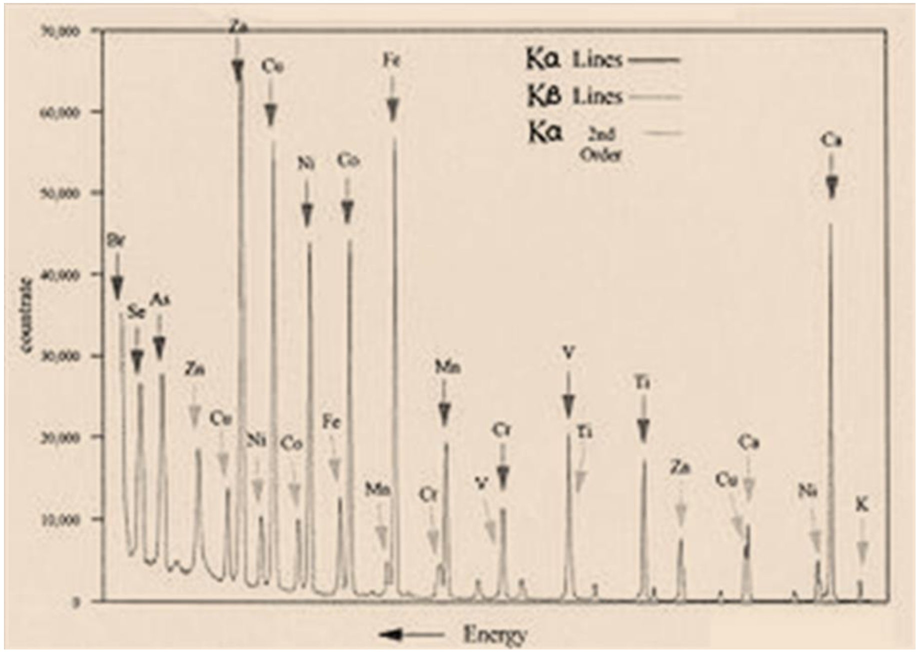


Thermal modelling of MOVs

Examination of this material suggested that a hot plasma formed in the conduction channel during the applied current pulse, and then rapidly cooled afterwards due to heat conduction to the surrounding ZnO grains.

Thermal modelling of MOVs

The altered material was examined for composition using XRF spectral analysis. Here's an example of an XRF spectrum:



Thermal modelling of MOVs

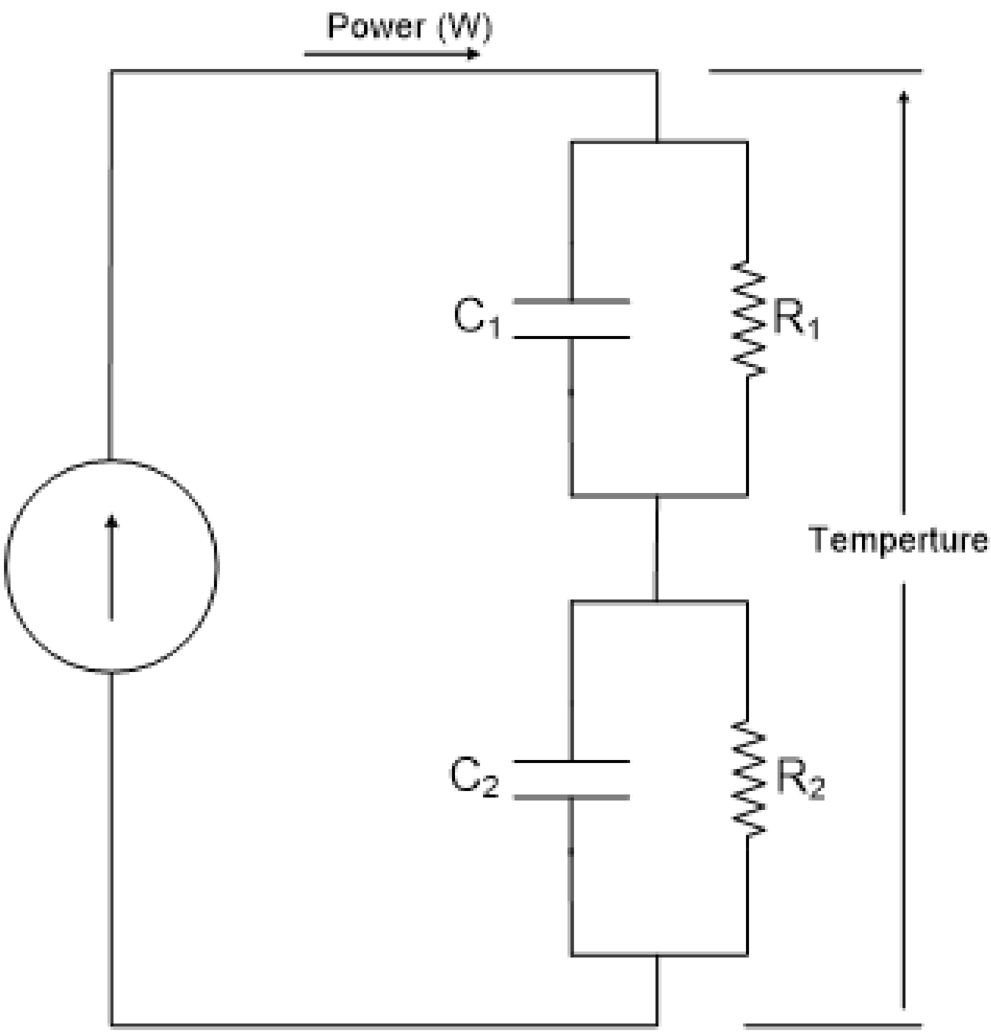
From the XRF results the new amorphous material was thought to require a local temperature around 1000 ^{o}C to form. Thermal modelling suggested that this temperature rise would occur if the pulse power was concentrated in about 2% of the MOV volume. But if the whole volume of the MOV participated, the calculated temperature rise would have been only 231 ^{o}C.

The results of Sargent and coworkers suggest that the criterion for failure of an MOV is a localized temperature rise to 1000 ^{o}C (or the vicinity thereof).

So for an MOV under consideration, we need to determine if a localized area might reach 1000 ^{o}C

To do that we begin with a thermal model.

In the thermal model, thermal paths can be modelled using an electrical circuit analog. To do that, volts are replaced by Temperature T(t) in ^{o}K; and current is replaced by Power P in watts. Keep this in mind as we look at the next slide, which shows the electrical circuit analog of an MOV.



R_1 and C_1 are the thermal resistance and thermal capacity of the area which might reach 1000 °C, and R_2 and C_2 are the thermal resistance and thermal capacity of the rest of the MOV.

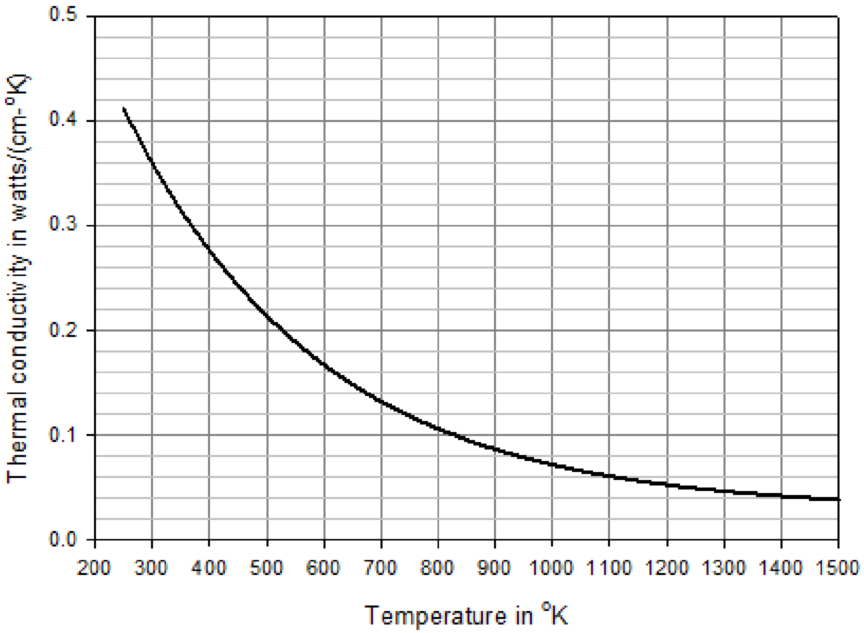
From the electrical circuit analogy we can write the thermal impedance *Z(ω) as*

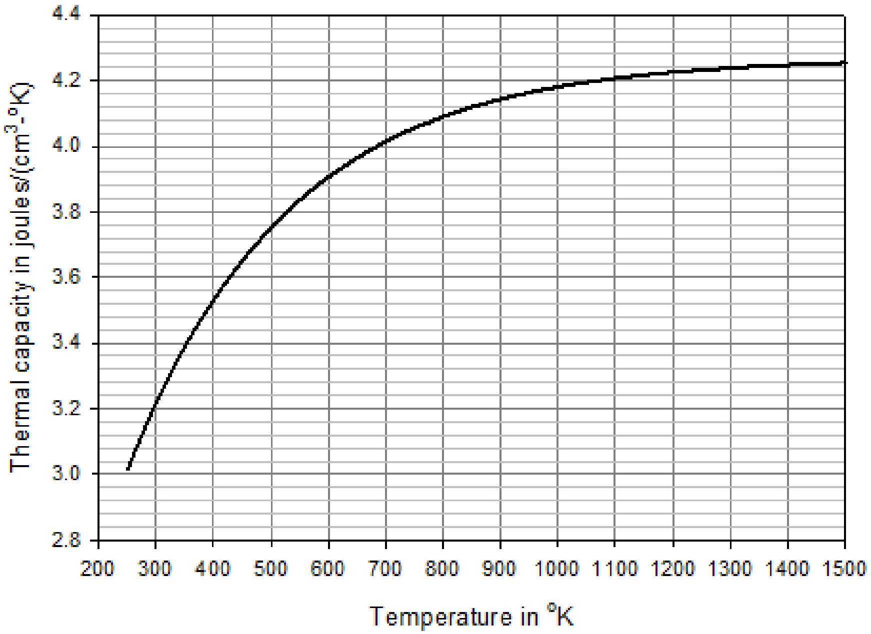
$$Z(\omega) = \frac{1}{C_1}\left[\frac{1}{s+d}\right] + \frac{1}{C_2}\left[\frac{1}{s+e}\right] \qquad (1)$$

Where we have used the ratios of thermal conductivity to thermal capacitance

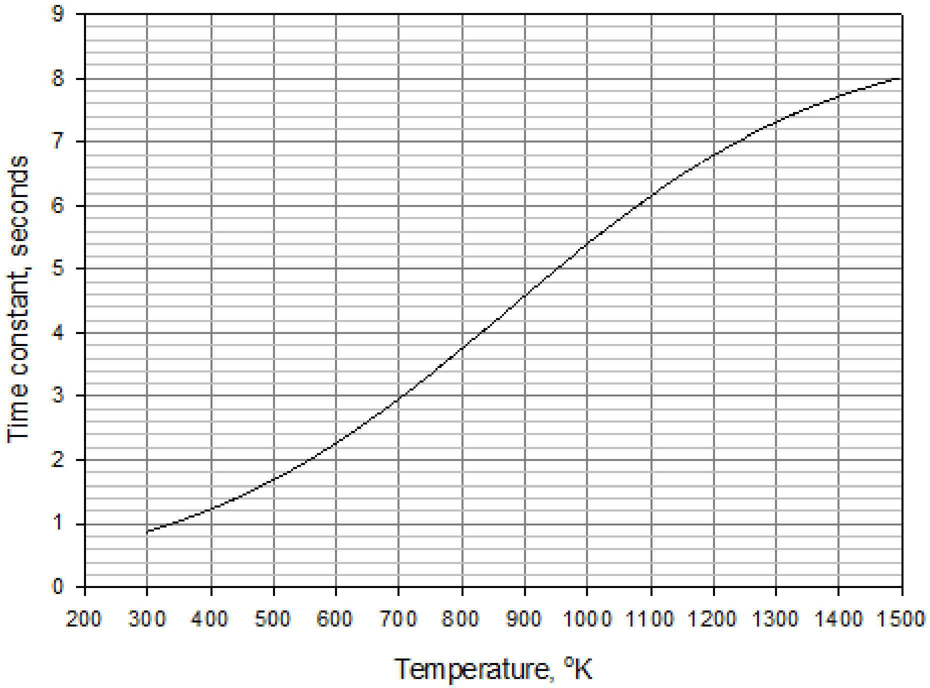
$d = \frac{\sigma_1}{C_1}$, $e = \frac{\sigma_2}{C_2}$, =jω

For zinc oxide (the basic component of MOVs), both the thermal conductivity σ and the thermal capacity C are functions of temperature, (based on data in [6]).





Due to the temperature dependence of the thermal conductivity and capacity, the thermal time constant is also a function of temperature



Computing the temperature rise of an MOV for single surges

Assume the power *W(t)* is given by

$$W(t) = I_p V_{mov}(i)[e^{-at} - e^{-bt}] \tag{2}$$

Where I_p is the peak current of the surge, and $V_{mov}(i)$ is the MOV voltage as a function of current.

In the frequency domain the power in equation (2) is

$$W(\omega) = \frac{I_p V_{mov}(i)[b-a]}{(s+a)(s+b)} \tag{3}$$

The temperature rise *T(ω)* is then

$$T(\omega) = W(\omega)Z(\omega) = \frac{I_p V_{mov}(i)[b-a](s+f)}{k(s+a)(s+b)(s+d)(s+e)} \tag{4}$$

In the time domain, *T(t)* is

$$T(t) = \frac{I_p V_{mov}(i)}{k}\left[\frac{(f-a)e^{-at}}{(d-a)(e-a)} - \frac{(f-b)e^{-bt}}{(d-b)(e-b)} + \frac{(b-a)(f-d)e^{-dt}}{(d-a)(d-b)(d-e)} + \frac{(b-a)(f-e)e^{-et}}{(e-a)(e-b)(d-e)}\right] \tag{5}$$

Where $f = \frac{C_1 d + C_2 e}{C_1 + C_2}$ and $k = \frac{C_1 C_2}{C_1 + C_2}$.

Example calculation – temp. rise for a single surge

As an example calculation, suppose we have a tower 80 m tall whose RRH 48 V DC feed we want to protect against lightning. Assume a negative lightning flash with 5% probability of occurring. Then from CIGRE TB549 [7], the amplitude is 80 kA and the action integral (I^2t) is 5.5×10^5 A^2s. If we assume a double-exponential waveshape, the corresponding time to half peak is calculated as 120 µs. The rise-time is generally not correlated with the duration, and from TB549 could reasonably be anything from 5.5 to 18 µs. Assume it is 10 µs. The waveform we have is then an 80 kA 10/120.

Example calculation – temp. rise for a single surge

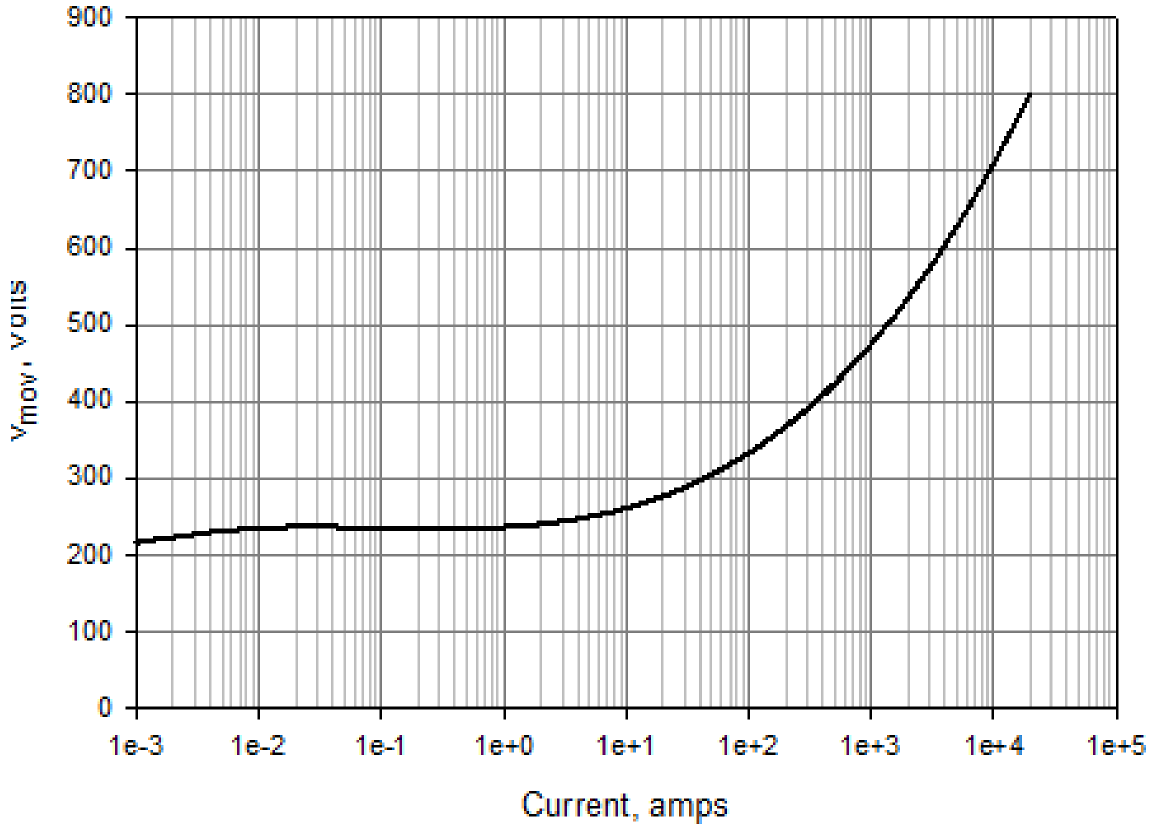
Using the calculations from the 2015 PEG presentation [5], an 80 kA 10/120 strike to an 80 m tower will result in a 17.5 kA 10/63 surge on the DC feed.

It appears that a 25 mm MOV rated at 20 kA with a Mcov of 130 V, would be appropriate for the application, so we'll select that.

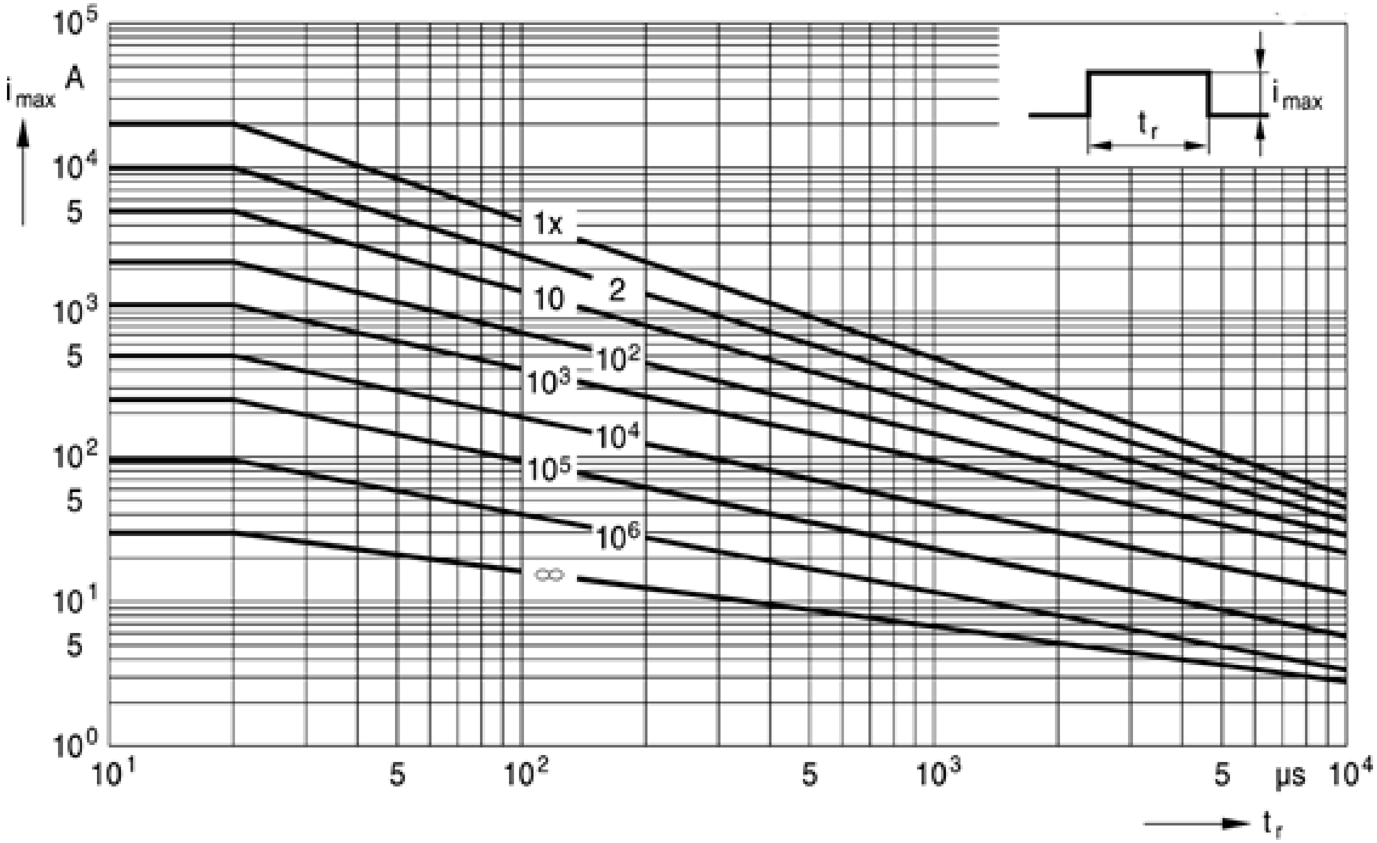
Example calculation – temp. rise for a single surge

For the calculation we need the V-I curve for the selected MOV. This curve depends on the device manufacturer, but the higher current region for a typical one is shown on the next slide.

Typical V-I curve for the selected MOV



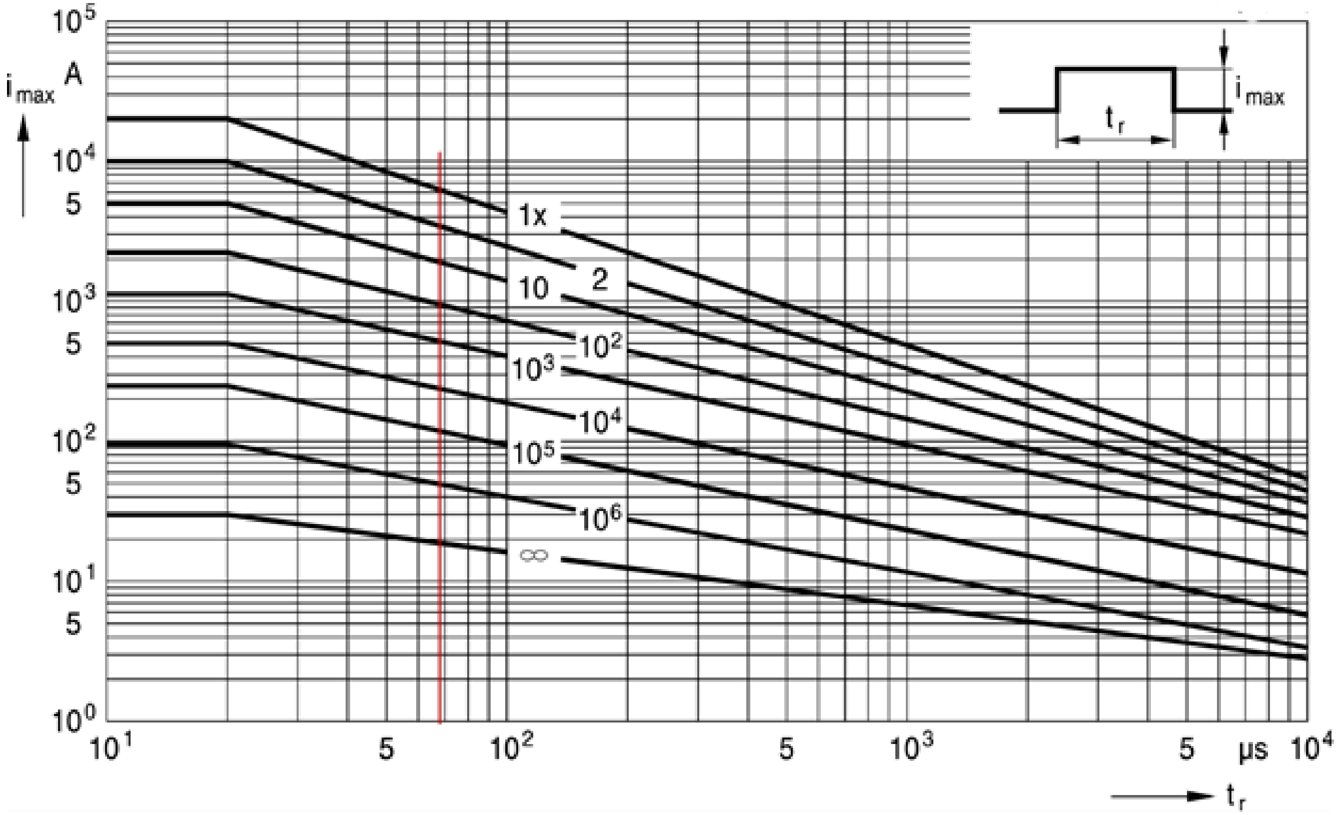
One other piece of information we need is the current vs. surge-width derating curves for the MOV. Here is one for the present case.



Ok – we've calculated the wire current as 17.5 kA, and the chosen MOV is rated at 20 kA, so we're good to go, right?

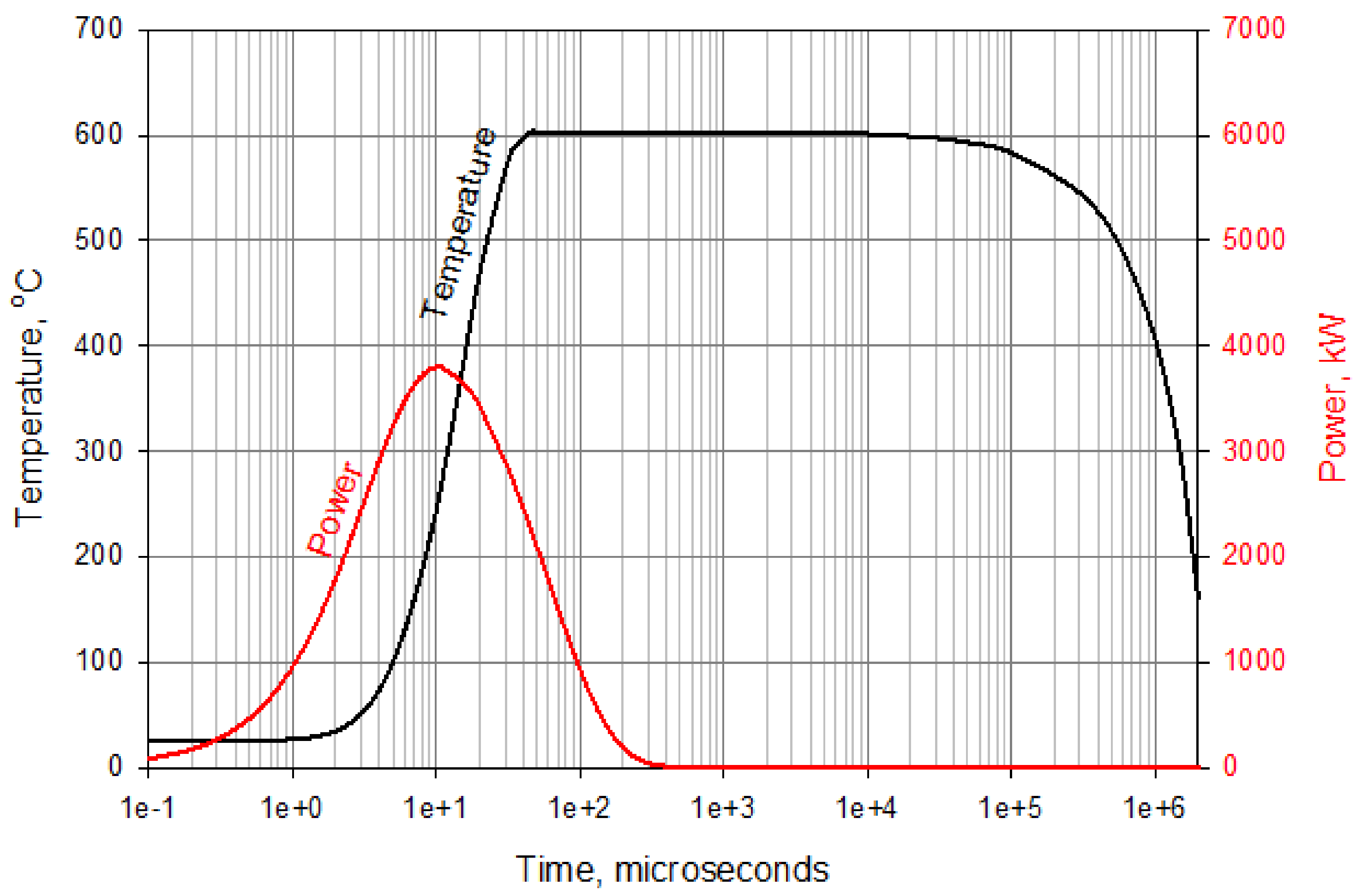
Well no. The 20 kA rating is for an 8/20 surge, and ours is 10/63. To find the rating for a 10/63 surge we need to consult the derating curves. To use these curves we need to convert the current-time relation of a double-exponential to that of a rectangular pulse of width t_r. The conversion factor is $t_r = (b - a)/ab$, where a and b come from the assumed double exponential, $e^{-at} - e^{-bt}$. For a 10/63 surge, $t_r = 69\ \mu s$.

If we now look at the derating curves and follow the red line at 69 µs up to the line for a single surge, Ip = Imax = 6 kA, which is substantially less than the 17.5 kA expected from an 80 kA strike.



If we want to handle the 17.5 kA surge on the dc feed we would need to put at least 3 of these devices in parallel so that no single device has to handle more than 6 kA.

OK, assume we've put enough devices in parallel so that a single device handles only 6 kA. For the device considered, the conductivity and heat capacity can be read from the graphs shown previously. Remembering that the surge is of the form $(e^{-at} - e^{-bt})$, for a 10/63 surge, $a = 1.39 \times 10^4$ and $b = 3.12 \times 10^5$. Then from equation (5) we can then calculate the temperature rise in one MOV for a 6 kA 10/63 surge, and plot the result (next slide).



700
600
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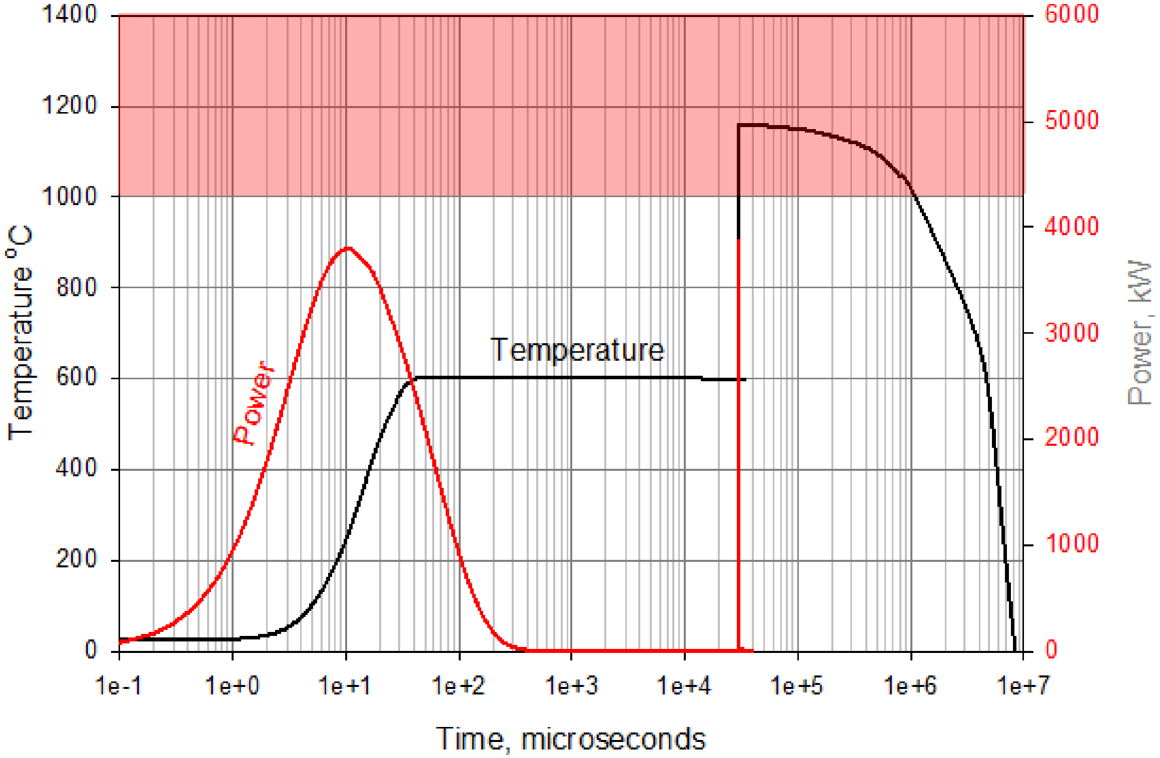
400
300
200
100
0
7000
6000
5000
4000
3000
2000
1000
0
Temperature, °C
Power, kW
Temperature
Power
1e-1
1e+0
1e+1
1e+2
1e+3
1e+4
1e+5
1e+6
Time, microseconds

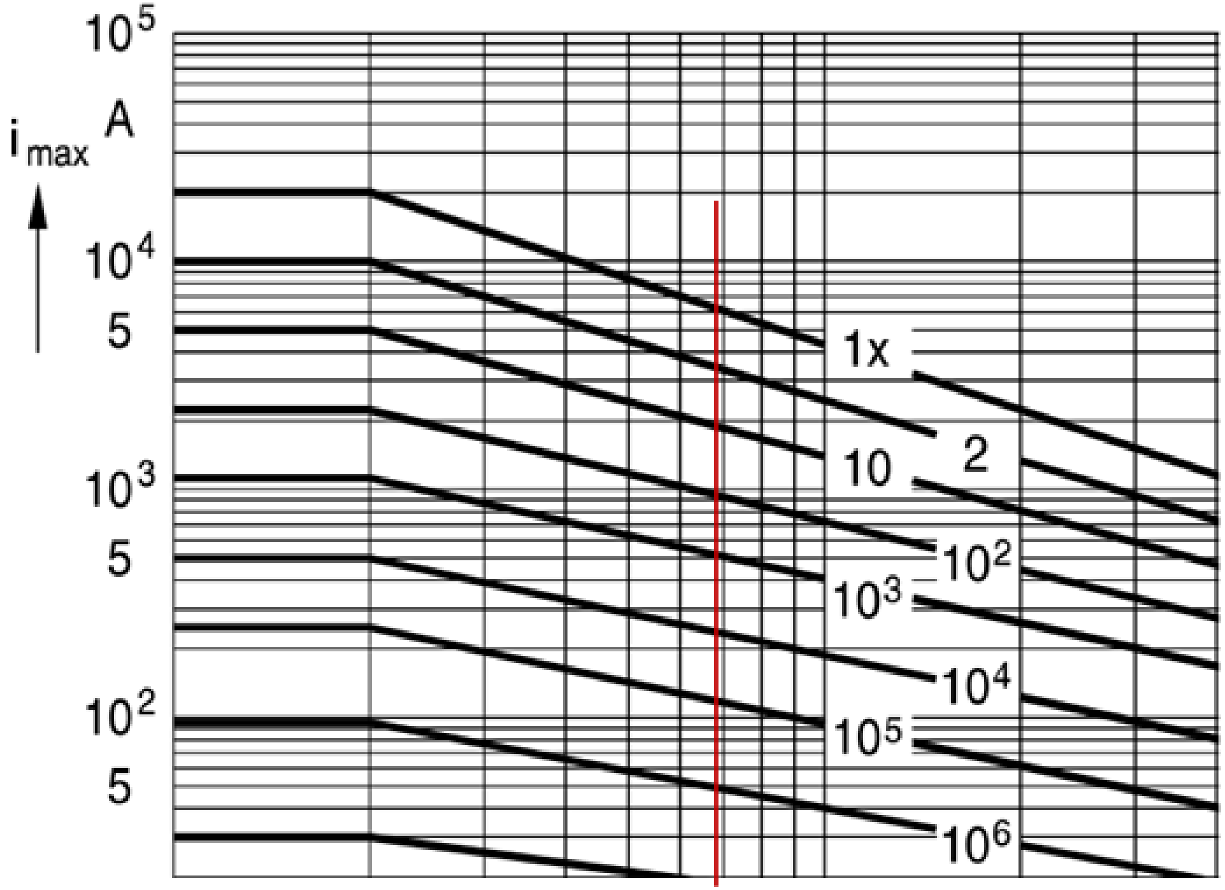
Example calculation – temp. rise for multiple surges

Here is what happens when the surge from the previous slide is applied to the MOV a second time after 30 ms.



The temperature rise in the previous slide is now in the red area above 1000 ^{o}C, where failure is expected. This result is consistent with the derating curves shown previously, which indicate that more than one surge at 6000 A would lead to failure (next slide)

Note that by following the red line up, 2 surges of 6 kA 10/63 is above the line for 2 surges on the graph



The derating curves also suggest that no failure would occur for 2 surges of 10/63 if I_{max} were reduced to 3400 A, which all else being equal would require doubling the number of paralleled devices.

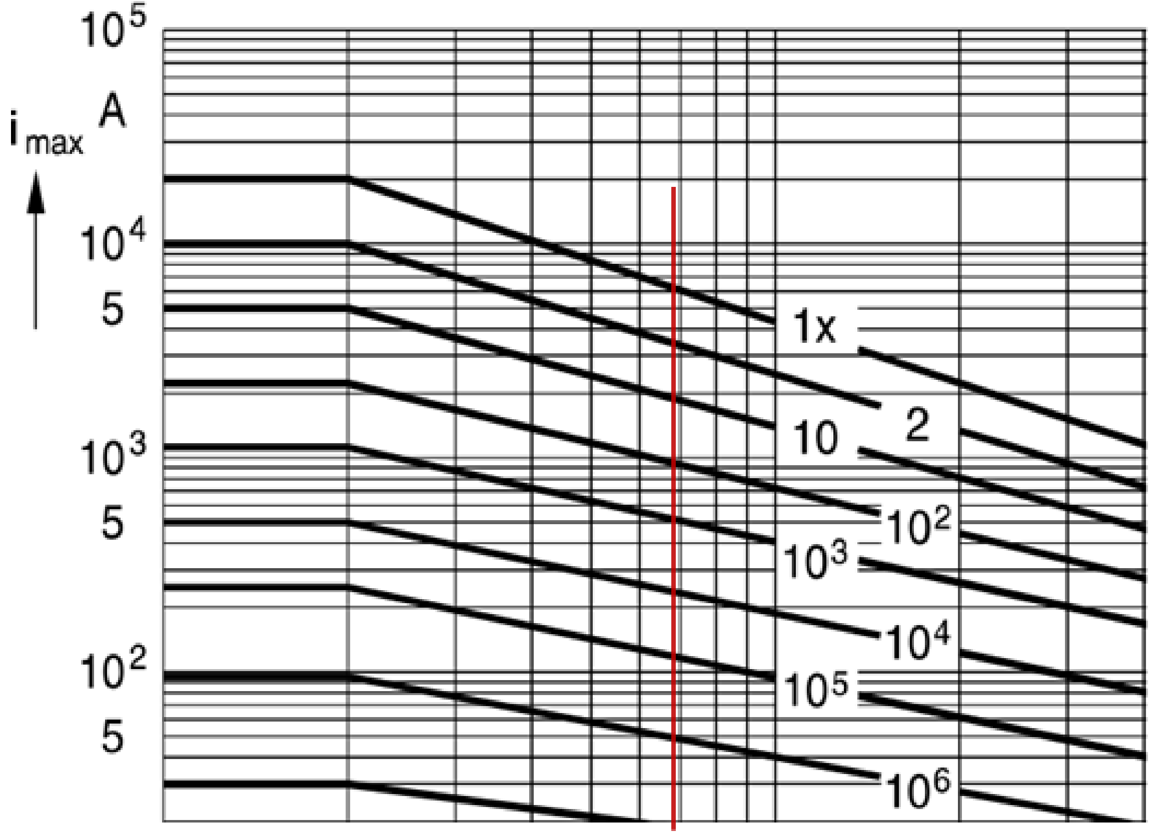
Calculations suggest that two surges of 3400 A 10/63 spaced 30 ms apart would result in a temperature rise of 630 ^{o}C, which is well below the 1000 ^{o}C assumed failure level.

So the derating curves are consistent with calculations as an indication of surge tolerance.

In an actual application many more than 2 surges will occur. The number of surges an SPD has to handle can be estimated by assuming n number of lightning flashes per year (from an isokeraunic map), having a number of strokes per flash x. If the SPD has y years of expected service, then the total number of surges is nxy.

So for example if the service life of the RRH equipment is 20 years, and 10 lightning flashes containing 5 strokes occur per year, then a total of 1000 surges could occur.

From the (enlarged) derating curves, running up the red line for 1000 10/63 surges, I_{max} would be limited to about 500 A.



Some comments

There are many of variables in this analysis, and conclusions could change depending on the assumptions used. In particular it was assumed that all surges have the same amplitude (to make it easy to use the derating curves). Generally there would be subsequent surges of lower amplitude, but assuming all surges have the same amplitude as the first one is a worst case, unless there is continuing current or initial continuing current.

Some comments

In the general case the procedure used to calculate temperature rise can still be used, if the exact sequence and characteristics of the first surge, subsequent surges, and any continuing current or initial continuing current is known.

The power input from each event in the flash is added to the previous one (with the appropriate time delay), and the cumulative temperature rise calculated. If the calculated temperature rise exceeds 1000 ^{o}C (or more conservatively, 800 ^{o}C) then failure can be expected.

Some comments

The calculation for an arbitrary sequence of surges and continuing current involves quite a bit of work, and is probably not worthwhile to do except for forensics.

Forensic studies have been done, for example that of Yang *et al* [8] with comments in [9], where the question was why a 40 kA rated MOV failed when subjected to a series of surges, none of which exceeded 26 kA, and continuing current.

Practical procedure for selecting an MOV

In the case of DC feeds to RRH there generally is no continuing current (see 2015 PEG presentation). In that case (or when there is no continuing current) the following procedure could be helpful for selecting an MOV:

- Consult an isokeraunic map of your area to estimate the number of lightning flashes, n, expected in a year
- Estimate the service life, y years, of the equipment to be protected
- Estimate the number of strokes, x, in the flash. If unknown, 4 or 5 is a reasonable guess

With that information, the total number T_L of surges expected is n times x times y.

Practical procedure for selecting an MOV

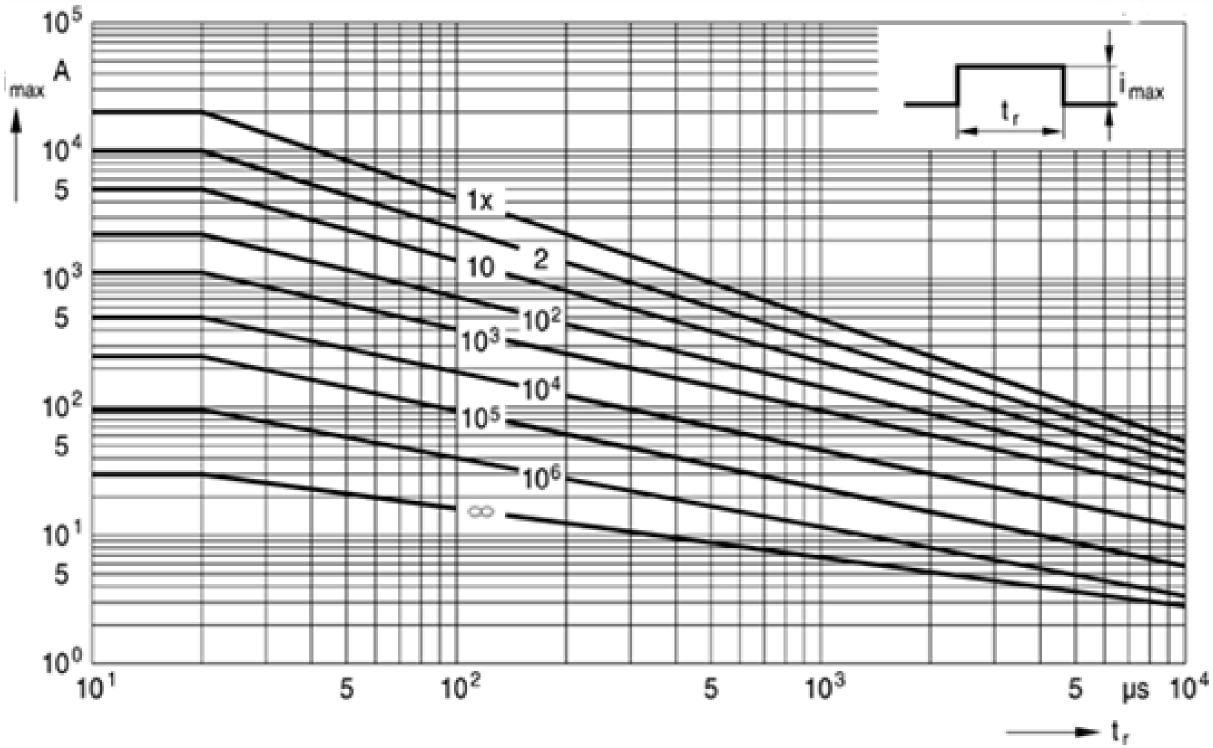
No continuing current present

Continuing, if there is no continuing current (for example the case of DC feeds to RRH considered above), the following procedure could be helpful for selecting an MOV:

- Determine the waveform of the surge to be protected against (because that determines t_r on the derating curves)
  - If a standard applies, use that
  - If the equipment is an RRH, reference [5] from the 2015 PEG meeting might be helpful
  - CIGRE TB549 is a useful reference
  - If none of the above works, a possible fallback is to assume an 80 kA 10/120 low probability stroke for extreme environments (like towers), or a 30 kA 5.5/75 median probability stroke for less exposed environments.
- Assuming your surge is a double-exponential like that in equation 2, calculate $t_r = (b – a)/ab$.

Practical procedure for selecting an MOV

Choose an MOV. On the derating curve for the MOV, go to t_r and move up to the curve for number of surges = T_L. Read across to the maximum allowed current I_{max}.

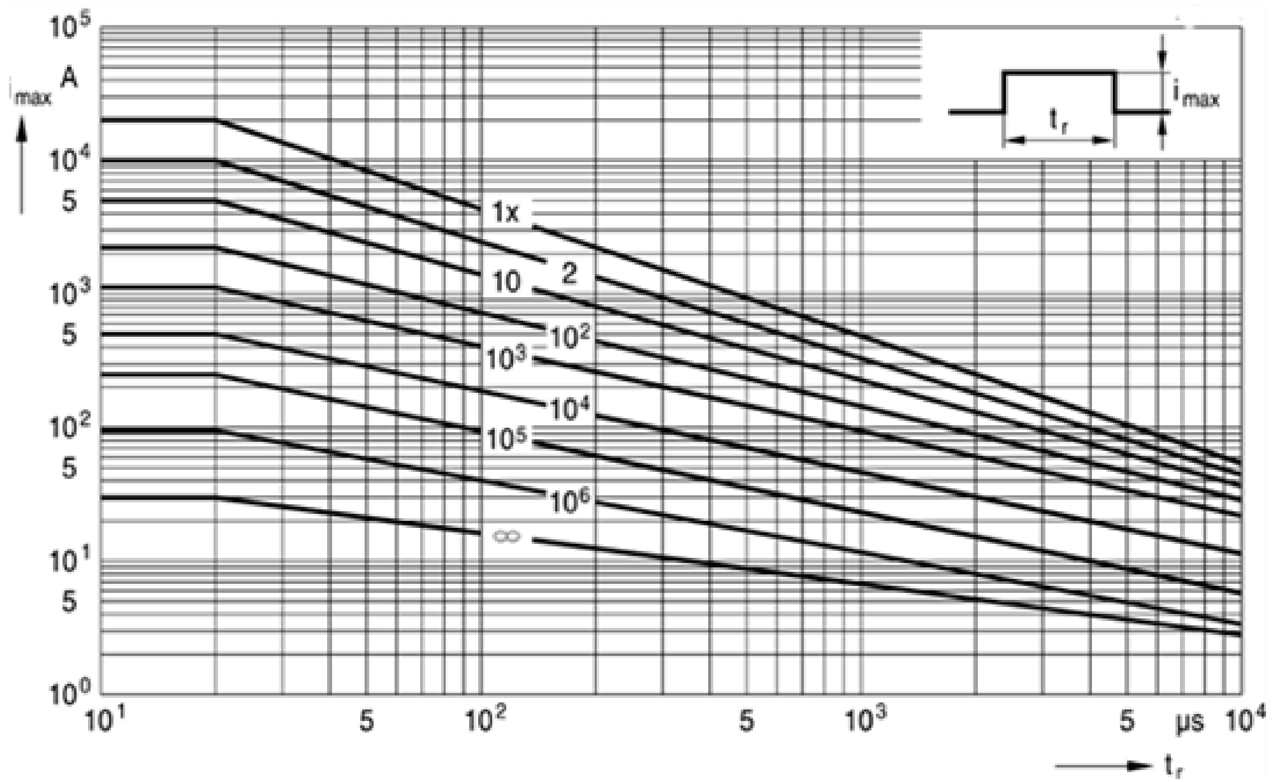


If I_{max} (per device) is greater than the peak current for the waveform you have assumed or calculated, you’re good to go. If I_{max} is less than the peak current for the waveform you have chosen, you will either need to parallel enough devices to handle the current, or choose a bigger MOV.

Continuing current present

Sometimes the continuing current is enough by itself to cause failure. To see if that is the case, approximate the continuing current by a rectangular pulse having the amplitude I_{max} and a duration t_r of the continuing current.

On the derating curve for the MOV, look for the intersection of I_{max} and t_r. If it is above the curve for a single surge, then failure will occur.



The bottom line…

In the case of MOVs, inhomogeneity in composition generally causes current surges to be conducted in a narrow channel. The confined surge causes a temperature rise which if it exceeds 1000 ^{o}C can cause failure. Failure in this sense is based on observable changes in the MOV.

Multiple burst surges can cause the temperature rise in the MOV to exceed 1000 ^{o}C due to heat accumulation, leading to failure of the MOV. That is why multiburst surge testing is important.

So that's some thoughts about MOVs.

There are also silicon clamping devices. They too can suffer from accumulated temperature effects. But silicon devices have a much different thermal time constant, and a different failure mode, so that's a story for another time.

References

[1] Berger, K., "Novel Observations on Lightning Discharges: Results of research on Mount San Salvatore," J. Franklin Institute, vol. 283, pp. 478-525, 1967.

[2] Bodle, D. W., A. J. Ghazi, M. Syed, and R. L. Woodside, Characterization of the Electrical Environment, Toronto: University of Toronto Press, 1976.

[3] Sargent, R. A., G. L. Dunlop and M. Darveniza, "Effects of Multiple Impulse Currents on the Microstructure and Electrical Properties of Metal-oxide Varistors," IEEE Transactions on Electrical Insulation, vol. 27, no. 3, p. 586, 1992.

[4] Rousseau, A., Zhang, X., and M. Tao, "Multiple shots on SPDs - additional tests," in Int'l Conf. on Lightning Protection (ICLP), Shanghai, 2014.

[5] Martin, A. R., "Power feeds to remote radio heads - what protectors need to deal with," in The Alliance for Telecommunications Industry Solutions Protecteion Engineers Group Conference, Monroe, LA, 2016.

[6] “Zinc oxide (ZnO) Debye temperature, heat capacity, density, melting point, vapor pressure, hardness”. Part of Subvolume B ‘II-VI and I-VII Compounds; Semimagnetic Compounds’ of Volume 41 ‘Semiconductors’ of Landolt-Börnstein - Group III Condensed Matter. Available: http://link.springer.com/chapter/10.1007/10681719_312 [7] CIGRE WG C4.407, "TB549 Lightning Parameters for Engineering applications," 2013.

[8] Yang, S. J., S. D Chen, Y. J. Zhang, W.S. Dong, J. G. Wang, M. Zhou, D. Zheng, and H. Y Hui , "Triggered Lightning Analysis Gives New Insight into Over Current Effects on Surge Protective Devices," www.ten350.com/papers/icae-conghua.pdf.

[9] Maytum, M. J. “CIGRÉ (Council on Large Electric Systems) Technical Bulletin (TB) 549 (2013) Lightning Parameters for Engineering Applications” ATIS PEG, Littleton, CO, 2014.

[10] Rakov, V. A., "Lightning Parameters of Engineering Interest: Application of Lightning Detection Technologies," in EGAT, Bangkok, Thailand, November 7, 2012.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Questions?