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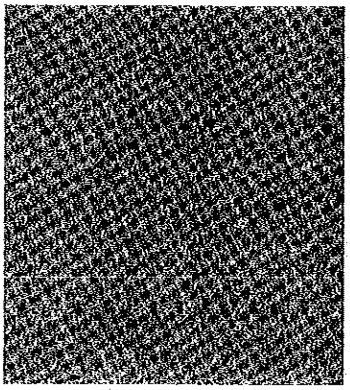

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1. INTRODUCTION

When lightning strikes the external lightning protection system of a building, most of the lightning current flows into the earthing system. But a part of the lightning current also flows in conductors inside the building, such as pipes and electric wires.

At the building entrance, which is the interface between lightning protection zone 0 and 1, all incoming lines must be included into complete lightning protection equipotential bonding. The active conductors of the ac supply mains must be connected to lightning current arresters. Inside the building, at the interfaces of lightning protection zone 1 and 2 and higher, overvoltage arresters that have a lower discharge capacity than lightning current arresters are used.

2. REQUIREMENTS FOR ARRESTERS

The primary lightning threat can be shown by three current components [1, 2]:

- the surge current 10/350 μs,
- the long-duration current 0.5 s,
- the surge current 0,25/100 μs.

All three components are injected currents.

If there is no detailed analysis of a structural system, it is assumed, that half of the lightning current will be discharged into the earthing system and half will be fed into the distantly earthed supplying systems (at the interface of the lightning protection zones 0 and 1) [1] (Fig. 1). Furthermore, it is assumed that this partial lightning current will be distributed equally on the supplying systems and also equally on the conductors of every system. These partial lightning currents on the supplying systems or their conductors are controlled at the interfaces of the lightning protection zones 0 and 1 by means of the lightning current arresters.

At the interfaces of lightning protection zones 1 and 2, and higher, additional protectors are necessary because of the remnant from the lightning current arrester and the overvoltages induced by the electromagnetic field of lightning and internal sources of interference (switching operations in the ac supply mains). These disturbances must be controlled by overvoltage arresters.

3. REQUIREMENTS TO LIGHTNING CURRENT ARRESTERS

The preferred lightning current arrester are spark gaps and metal oxide varistors. The advantages or disadvantages of the chosen components must be taken into account. The advantage of the metal oxide varistors is that a follow current can not occur. However, varistors have a disadvantage that their maximum allowable surge current is much less than for sark gaps. Table 1 gives the maximum allowable surge current for a single varistor; a single spark gap can survive a peak current of 25 kA on a 10/350 μs wave.

diameter of the metal oxide varistor disk				
mm	32	40	60	80
maximum surge current, 10/350 μs				
kA	1	2	3	5

Table 1: Current rating of metal oxide varistors for surge currents 10/350 μs [3].

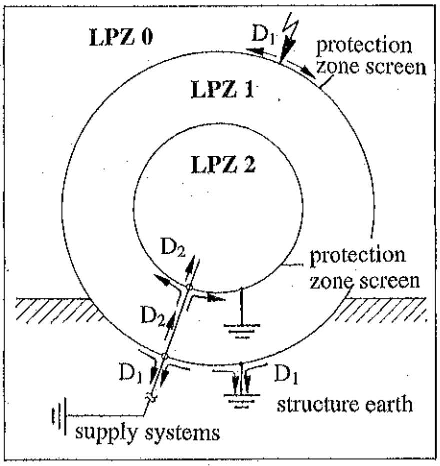

Figure 1: Lightning Protection Zone Concept

LPZ: Lightning Protection Zone
Disturbance D_1 traveling out of building:
Lightning current or partial lightning current, containing surge current 10/350 μs,
Long duration current 0,5 s, and surge current 0,25/100 μs
Disturbance D_2 inside building:
Open circuit surge voltage 1,2/50 μs, short-circuit surge current 8/20 μs
fictive internal resistance of the source of interference typ. 2 Ω

If a varistor were used as a lightning current arrester, it could not shorten the tail of lightning surge current 10/350 μs, so that a long-duration surge current shape also reaches the downstream overvoltage arresters. This complicates the coordination of the lightning current arresters with the downstream overvoltage arresters and with the electronic equipment to be protected [4].

The main advantage of the spark gaps is their high current carrying capacity. A single gap is able to discharge surge currents 10/350 μs up to 25 kA without changes in their characteristic that impairs functionality. After spark over of the spark gap, the arc voltage is a few tens of volts, which relieves the downstream overvoltage arresters almost completely. This gives a great advantage concerning the coordination of the arresters. Unfavourable is the relatively high sparkover voltage approx. 4 kV, and, above all, the short circuit that will arise in the low-voltage ac supply mains after spark over, in connection with a high follow current.

Overcoming these disadvantages of spark gaps would make them a highly desirable component for lightning current arresters.

4. BASIC POSSIBILITIES TO INFLUENCE THE CHARACTERISTICS OF SPARK GAPS

Simply expressed, spark gaps of lightning current arresters have the specific task to "discharge" the energy that is in the surge, and thus to relieve the downstream overvoltage arresters, devices and systems. Furthermore, they must ensure that the follow current from the mains will be safely extinguished at the next current zero crossing.
Concerning the construction of these components, the following requirements apply:

- The impulse sparkover voltage of the gap must be lower than the insulation strength of the system to be protected. Because of coordination with the downstream arresters, this sparkover voltage should be as low as possible. This is mainly realized by a short distance between the electrodes.

- Like a circuit breaker, the spark gap must be able to safely extinguish follow current from the mains. For this reason, it is advantageous to generate a relatively high arc voltage.

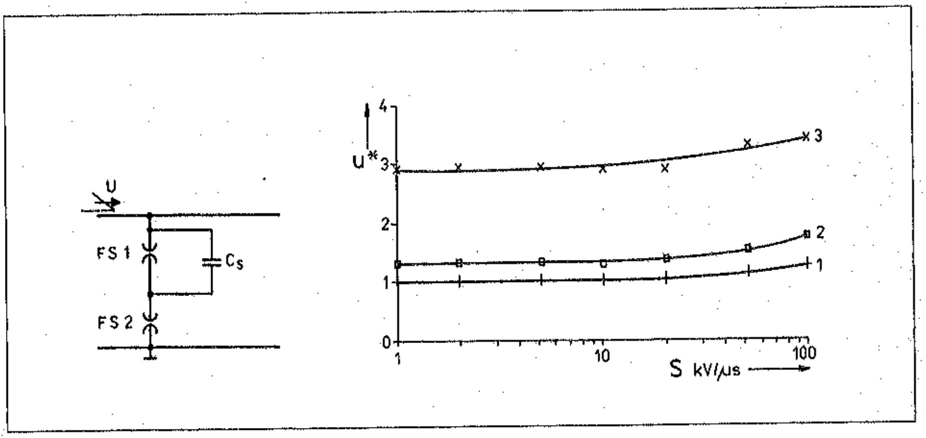

Figure 2: Capacitive Control of Double Spark Gaps
FS1, FS2: component spark gaps
C_S: Controlling capacity
1: Individual spark gap
2: Controlled double spark gap
3: Uncontrolled double spark gap

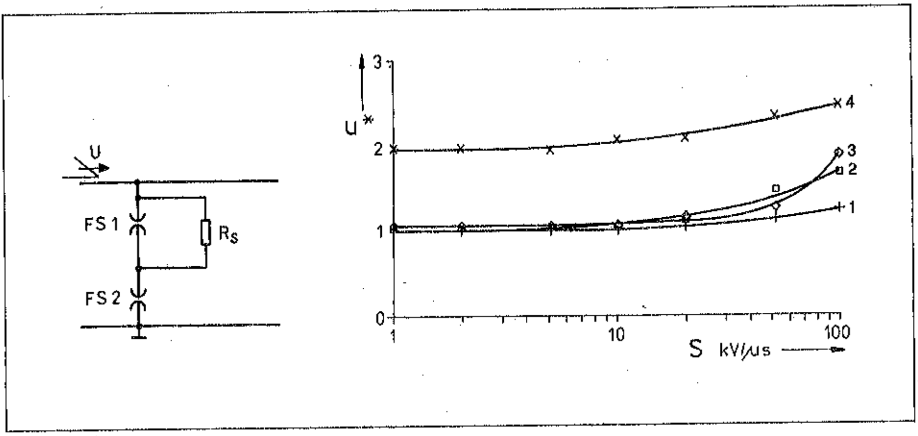

Figure 3: Ohmic Control of Double Spark Gaps
FS1, FS2: component spark gaps
Rs: Control resistance
1: Individual spark gap
2: Controlled double spark gap
Rs = 270 Ω
3: Controlled double spark gap
Rs = 1000 Ω
4: Uncontrolled double spark gap

Equation (1) gives the relationship between the components of the arc voltage, U_B:

$$U_B = (U_A + U_K) + (l \bullet E) \qquad (1)$$

U_A: voltage drop at the anode,
U_K: voltage drop at the cathode,
l: length of the arc,
E: electric field in the arc.

According to equation (1), there are three possibilities for decreasing the arc voltage, U_B.

- Increase the arc length l. This can be realized by a longer electrode distance, or by discharge horns.
- Increase the field strength E of the arc (for example, by cooling).
- Mulitply the anode and cathode voltage drop U_A and U_K by subdividing into several different arcs in series. This is especially advantageous for the quenching capacity, as a multiplication of the arcs also means a multiplication of the arc extinguishing voltage.

This short specification makes clear that there are partly contrary requirements. Only if it is succeeded in disentangling the complex requirements by a suitable separation of the functions, can optimal characteristics be achieved. The development of special spark gaps in series with partly different characteristics, makes it possible to separate the functions.

The series connection improves the follow current extinguishing capacity. However, there is the disadvantageous effect of the increase in sparkover voltage. Suitable ohmic or capacitive controlling techniques, however, can cause a very unequal distribution of an overvoltage among the individual spark gaps, so that the operating voltage of the complete arrangement will almost correspond to that of one individual component [3]. Fig. 2 shows a surge characteristic of capacitively controlled multiple spark gaps.

For comparison there are also shown in Fig. 2 the characteristics of a single spark gap and of a double spark gap. The capacitive ratio for the double spark gap is about 1 : 10. One can state that the sparkover voltage of the double spark gap only rises by about the factor 1.15 compared with the single spark gap.

Fig. 3 shows the surge characteristics for an ohmic control. Also in this case very low surge sparkover voltages can be reached. By a suitable choice of the control components the characteristic can not only be lowered, but it can also be influenced in its rise (curve 3 in Fig. 3) at large values of du/dt.

Theoretically, it is possible to realize the capacitive and the ohmic control by external components from the spark gaps. Practically, one encounters the problem of a considerable mechanical and thermal stress that occurs when a lightning current arrester sparks over, against which these components can hardly be protected. For practical application, an integrated solution is more advanteous, in which the spark gap control is a part of the whole construction. The geometrical formation of the electrodes (such as, diameter and profile), as well as the use of different dielectrics in the individual spark gaps, makes it possible to realize an integrated capacitive control. A resistive control can be achieved by suitable conductivities of the insulating materials between the electrodes.

After the spark gap conducts, there is a follow current in the gap from the ac supply mains. This follow current can have peak values of a few up to some ten kiloamperes, depending on the available fault (short-circuit) current from the mains. This follow current must be automatically extinguished by the spark gap alone. This is especially important in mains with a relatively small available short-circuit current, because in these cases the pre-fuse may not open within a half-cycle of the ac follow current.

If lightning current arresters that contain a spark gap have a breaking capacity in the range of several kiloamperes, comparable to that of circuit-breakers, the safety of the utility network is considerably increased.

For the breaking capacity, a good cooling of the switching arc is necessary. Thus a rapid deionization of the switching gap directly after the natural current zero-crossing will be reached and a reignition under the influence of the sinusoidal mains voltage will be avoided. For the high-current phase, a good cooling means a high arc voltage. The consequence is that the amplitude of the short-circuit current will be limited.

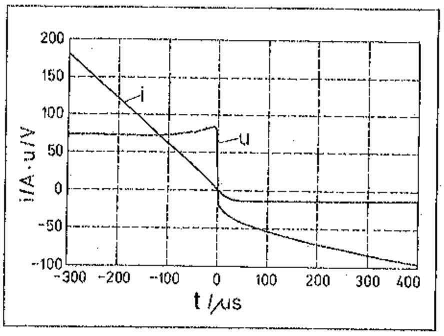

Figure 4: Switching Oscillogram of a Single Spark Gap at Current Zero Crossing

An adequate cooling of the arc can be reached by different methods.

- Special insulating materials emit gases with high heat conductivity (like H_2) under the thermal influence of the arc. This "hard gas technology" has already been applied for many years in the construction of circuit breakers.
- By the motion of the arc, by using the electro-dynamic forces, the cooling effect can be considerably increased. Additionally the electrodes will be thermally protected. Within the short duration of the arc point on an electrode section, melting will be negligible and so reignition caused by glow emission after the extinction of the arc will be avoided.

By the proper choice of material (e.g. high melting temperature, surface roughness) and the design of arc conducting devices, this effect can be intensified and thus the sensitive zones of the spark gap will be conserved.

Doubling the anode and cathode voltage is a decisive advantage of double spark gaps. Owing to the different mobilities of the positive and negative charge carriers of the arc plasma, one will get a zone of increased dielectric strength in the gap immediately after the current zero crossing. This so-called immediate reinforcement very much improves the switching capacity, especially in case of unfavourable mains conditions (low cos φ, high natural frequency during transient oscillation).

All the possibilities discussed in this section will allow the engineer to directly influence the intended characteristics of a spark gap. The variety of influencing possibilities and the interaction of the individual mechanisms, however, make it unlikely to get an effective solution by "trail and error". For a successful work, the use of numerical models to imitate the principial characteristics of a spark gap is a great advantage.

5. COMPUTER AIDED SIMULATION OF SPARK GAPS

For lightning current arresters containing a spark gap it is favourable to subdivide the whole simulation into two steps. In a first step, one must simulate how the spark gap sparks over under the influence of the incoming surge voltage, and in the second step, how the mains follow current will be safely extinguished.

So-called hybrid models have proven for the simulation of the operating and arc-extinguishing behaviour. Based on experimentally determined surge characteristics, the operating dynamic will be simulated and by means of these starting values, under application of Toepler's Spark Law, the arc-extinguishing period can be calculated.

A determination of the necessary geometric quantities and of the Toepler constant is possible without great efforts. If the additionally relevant parasitic components are considered for the simulation, a sufficient accuracy can be achieved [5]. It is, however, much more complicated to calculate the quenching of the follow current. The main reason is the complicated process, characterizing such a high temperature plasma. There are detailed works concerning the problem of modeling the switching arcs in circuit breakers [6, 9]. But there is less experience in how far these correlations can be applied to the quenching of a spark gap.

The simulation of these processes would also be possible by two different methods:

- The exact treatment of the physical relations describing an arc. These physical-mathematical models need a series of data that are difficult to determine, and due to their enormous complexitivity, they are only conditionally suitable for the development work. Furthermore, one must take into account that a stochastic phenomenon like an arc is very difficult to be described by a deterministic model.
- The treatment of the switching arc by means of an integral energy balance. The advantage is, that the individual, very complex causal relations are not considered, but only their effects on the integral balance quantities of the system.

The second method is described in the literature as the bipolar model [6, 9]. Especially the formulation with a twofold modified Mayr-equation [6], in which case as well the power dissipation P_V as also the thermal time constant τ as functions of the time variable conductance G(t) are taken into consideration, allows a sufficiently exact calculation of the quenching behaviour:

$$\frac{1}{G(t)} \cdot \frac{dG(t)}{dt} = \frac{1}{\tau(G)} \cdot \left[\frac{u_B \cdot i}{P_V(G)} - 1 \right]$$

u_B: arc voltage
i: arc current
G: conductance of the arc
$P_V(G)$: power dissipation of the arc
$\tau(G)$: thermal time constant

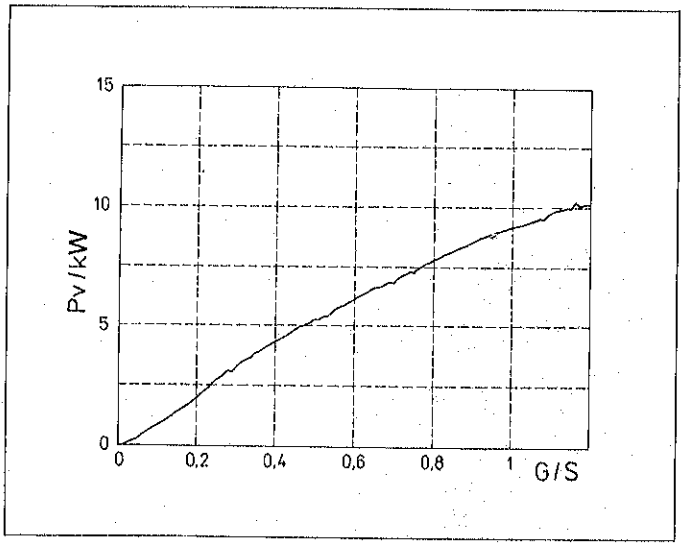

Figure 5a:
Power Dissipation, P_V, as a Function of the Conductance, G

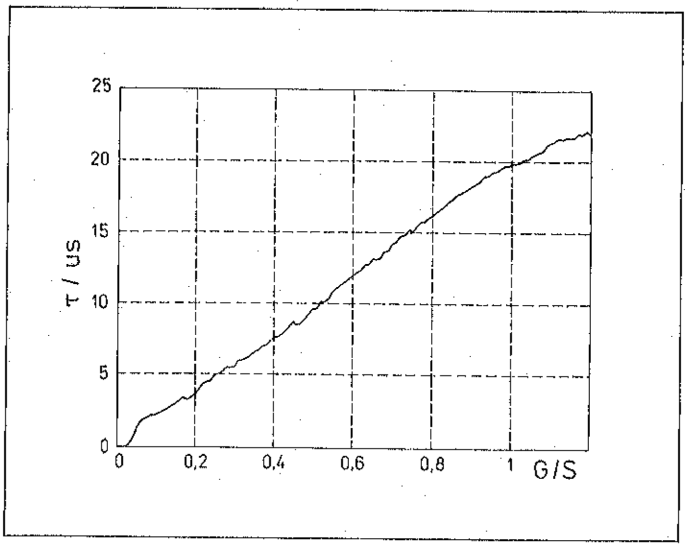

Figure 5b:
Thermal Time Constant τ as a Function of the Conductance, G

The characteristic functions $P_V(G)$ and $\tau(G)$, are determined by special switching oscillograms, so-called current zero-crossing oscillograms . Thereby only the time range directly around the natural current zero crossing (some hundred micro-seconds) is considered (Fig. 4) as only this range is essential for the dynamic behaviour of the arc and thus for the switching behaviour [7]. Due to the stochastic processes of the arc, it is necessary to carry out a number of switching tests on a wide range of currents. Special methods have been developed to evaluate these test results which take into account the stochastic processes of the arc [7]. As results the characteristics $P_V(G)$ and $\tau(G)$ can be further evaluated by derived mathematical functions. Fig. 5a and 5b show these results for a single spark gap.

The three quantities, power dissipation $P_V(G)$, conductance $G(t)$, and the rate of change of conductance $dG(t)/dt$ describe the energetic relations in arcs during the switching process, thus making it possible to evaluate constructive variants. As these functions $P_V(G)$ and $\tau(G)$ are characteristic for an individual spark gap, it is possible to calculate the switching behaviour under any mains conditions. Thus, for example, the influence on switching capacity of the following three variables can be calculated in a cost-effective way: mains voltage, power factor (cosφ), and natural frequency of the transient voltage [8, 9]. An example for a follow current quenching behaviour is shown in Fig. 6a and 6b.

Fig. 6a shows the successful extinguishing of follow current at t = 16,7 ms. In Fig. 6b, the gap is unable to extinguish follow current: the arc in the gap restrikes after each zero-crossing of the mains voltage and current.

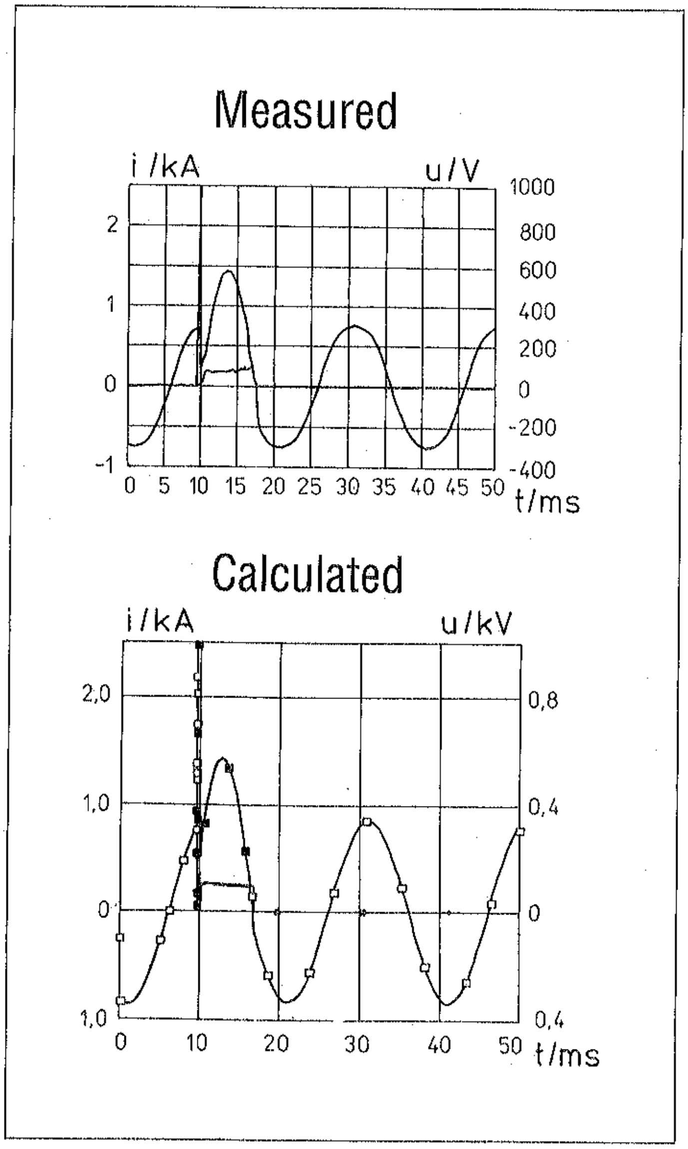

Figure 6a:
Successful Quenching of the Mains Follow on Current

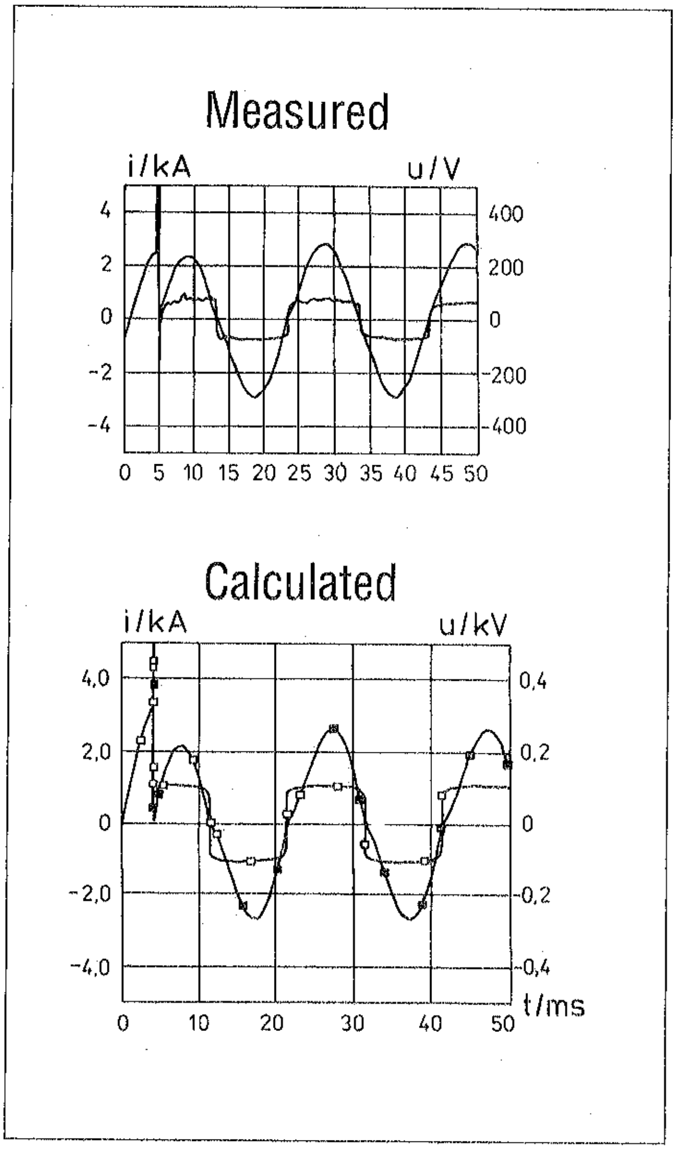

Figure 6b:
No Interruption of the Mains Follow on Current

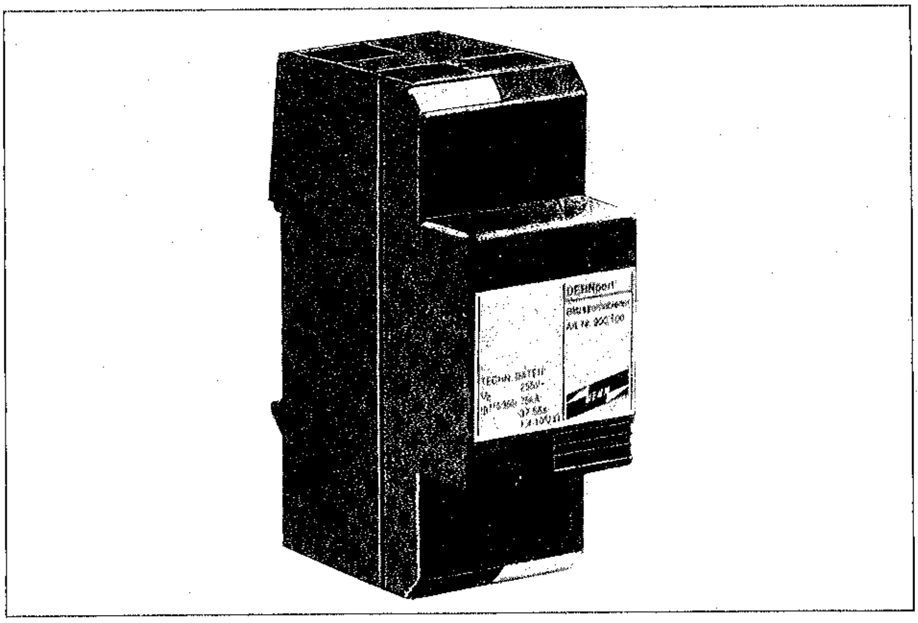

Figure 7: Lightning Current Arrester DEHNport

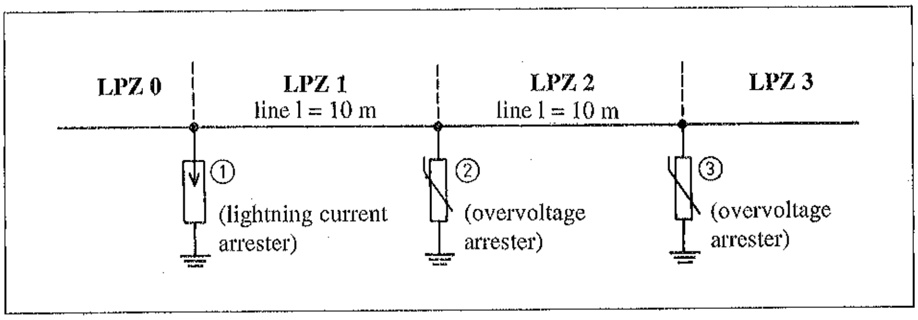

Figure 8: Stepped Application of Arresters

LPZ: Lightning Protection Zone
1 Spark Gap
2 Varistor, Disc Diameter d = 40 mm
3 Varistor, Disc Diameter d = 20 mm

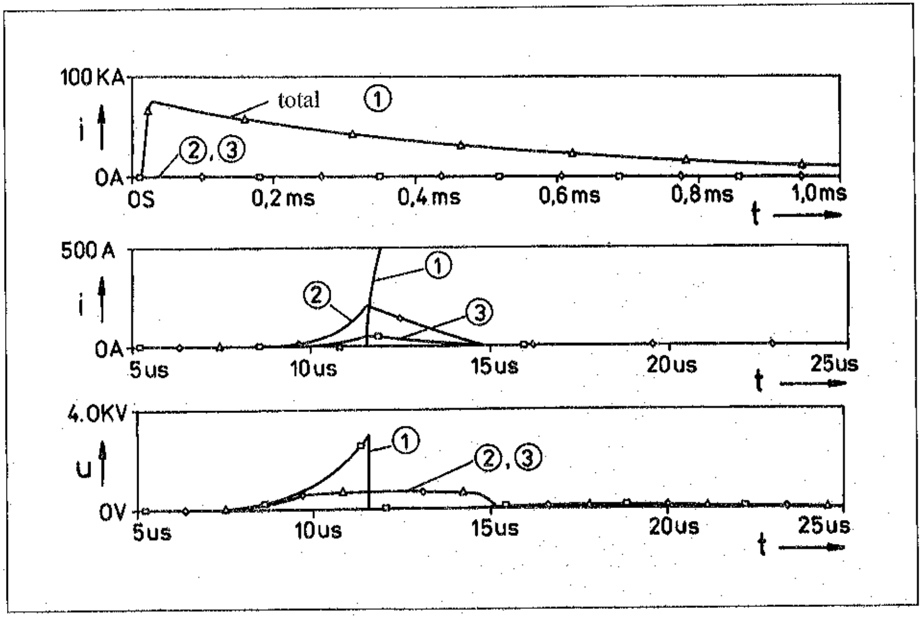

Figure 9: Coordinated Effects of Lightning Current Arrester **1** and Overvoltage Arresters **2** and **3**

6. PRACTICAL APPLICATION

Fig. 7 shows a lightning current arrester containing a spark gap, that has been conceived under the application of the described computer-aided design. This compact protector is able to discharge lightning currents 10/350 µs up to 75 kA. The follow current quenching capacity of this arrester is a few thousand amperes; the limit breaking capacity (twice without damage) is approximately 10 kA, the sparkover voltage is about 3 kV.[1]

Fig. 8 shows a typical set of one lightning current arrester and two overvoltage arresters that protect electronic equipment inside a building. During a simulated 10/350 µs surge with a peak current of 75 kA, the distribution of currents in the three arresters is shown in Fig. 9. The spark gap in the lightning current arrester conducts at t = 11,5 µs; thereafter essentially all surge current is carried by this spark gap.
After spark over of the spark gap in the lightning current arrester, an extensive relief of the downstream overvoltage arresters occurs. Due to the low arc voltage of the spark gap, this relief will also be maintained, even if an overvoltage arrester with a too low protection level should be used. Moreover the downstream overvoltage arresters will only be loaded by currents of a shape comparable to about 8/20 µs. This makes it possible to dimension and to test all overvoltage arresters down to the vulnerable equipment by means of a hybrid impulse 1.2/50 µs / 8/20 µs [4], which is considered as a standard test in the EMC community. Thus a close combination of lightning protection and EMC is given.

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[1] This lightning current arrester is part of a well co-ordinated family of overvoltage protection devices, which ensure comprehensive lightning and overvoltage protection.

LITERATURE

[1] DIN VDE 0185 part 103 (Draft)/12.92: Protection against lightning electromagnetic fields (LEMP). Part 1: General principles. Identical with IEC 81 (Sec) 44.

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[9] Kopplin, H.: Mathematische Modelle des Schaltlichtbogens. etzArchiv, Bd. 2 (1980) 7, paper 209-213.

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We are sorry, but in the present issue of our publication there are some misprints. Please note the corrections:

Page 2, collumn 2, section 1, line 9:
"sark gap" replace by "spark gap"

Page 2, collumn 2, section 1, penultimate line:
"25 kA" replace by "100 kA"

Page 2, collumn 3, section 2, line 4:
"25 kA" replace by "100 kA"

Page 3: Please add the following explanation to figures 2 and 3:
u*: Sparkover voltage, normalized to the sparkover voltage (with the steepness of 1 kV/µs) of a single gap

Page 3, collumn 1, section 1, equation:
"(1 • E)" replace by "(I • E)"