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BASIC PROBLEMS AND SOLUTION OF THE ENCAPSULATION OF A LOW–VOLTAGE SPARK GAP WITH ARC SPLITTER CHAMBER

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The main disadvantage of horn spark gaps resulting from the blow-out of hot ionised gases in case of lightning impulse and follow currents is discussed for modern and compact DIN rail mounted arresters. The technical problems of fully encapsulated horn spark gaps are revealed. Based on technical specifications, basic calculations for the required arc voltages and the thermal loads were made in advance for dimensioning the arc splitter chamber and the arc area of the spark gap. A method to fully encapsulate such spark gaps is proposed and its efficiency is described based on experiments with different arrangements and loads.

K e y w o r d s: horn spark gap, arc splitter chamber, extinguisher, methods for encapsulation, follow current limitation

1 FUNCTIONS OF LIGHTNING CURRENT ARRESTERS AND MODE OF OPERATION

Surge protective devices which are mainly used as DIN rail mounted devices in low-voltage installations and are directly installed at the entrance point of the power supply lines into buildings or systems are also referred to as lightning current arresters (SPD type 1). They are used for lightning equipotential bonding and to reduce high-energy conducted interference. For this reason, they must be able to discharge high-energy lightning currents of $10/350\,\mu$s wave form and injected impulse currents of $8/20\,\mu$s wave form several times and must at the same time maintain a low voltage protection level.

Sufficient energy coordination with downstream surge protective devices in sub-distribution boards (SPD type 2) or on terminal equipment (SPD type 3) must be ensured to prevent these so-called surge arresters from being overloaded.

If lightning current arresters operate due to a surge pulse or a potential rise, there is a low-impedance connection between the active phases and equipotential bonding (PE, PEN) and the so-called mains follow current is flowing through the arrester after the discharge process. Lightning current arresters must considerably limit and quickly extinguish this follow current so that upstream overcurrent protective devices do not trip and mains power failure is prevented.

The electrodes of todays encapsulated lightning current arresters with a high follow current extinguishing capability are often spaced at several millimetres. These great distances are due to the presently used principles to generate a high arc voltage. These arresters require complex trigger circuits to ensure sufficient energy coordination with downstream surge arresters.

When using a spark gap with divergent electrodes (horn arrester) and connected arc splitter chamber, the ignition and arc extinction area are separated. A very small electrode spacing in the ignition area can be selected for this arrangement. This allows space-saving triggering by simple means and excellent energy coordination.

Horn arresters are based on the efficient dc extinguishing principle and can therefore be used in dc and ac systems to control lightning and follow currents.

Until now a major disadvantage of horn arresters with arc splitter chamber was that hot ionised gases are blown out in case of lightning and follow current load, making it difficult or even impossible to use horn arresters in low-voltage installations.

Based on the results of theoretical and experimental tests, this paper shows that by taking adequate measures in the lightning current horn arrester high follow current limitation and arc extinction can be achieved despite of the full encapsulation.

2 DISADVANTAGES OF FULL ENCAPSULATION

It is known from extensive tests with covered arcing chambers in switching devices [1] that the arc velocity decreases in relation with an increasing degree of covering of the arc splitter chamber, the arc division is delayed or impeded and the stability of the arc behaviour in the arc splitter chamber is reduced due to arc backs.

These effects automatically lead to a delayed arc voltage build-up and an unstable arc voltage, resulting in high let-through currents and integrals. This heavily stresses the spark gap with arc splitter chamber, requires the use of high-strength materials and increases the arrester size.

Moreover, one of the most important goals of a lightning current arrester, that is to ensure a stable power supply, is at risk.

Due to the encapsulation of a blow-out arrester the energy is almost completely converted into heat within the arrester if mains follow currents are interrupted and

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the arrester is loaded with lightning impulse currents. In addition to the one-time power conversion and the first heating of the components it must be noted that cooling of the components is delayed. In case of a quick sequence of loads within some minutes as required by the DIN EN 61643-11 [2] standard, the energy input in the arrester adds up. When dimensioning the spark gap components, a reserve must be provided even in case of an excellent follow current limitation of the arrester and thus low energy conversion.

In addition to the requirements resulting from the interruption of mains-frequency follow currents, it has to be observed that the arrester also has to control the injected lightning impulse currents. In particular in case of small sizes, the encapsulation leads to additional mechanical loads due to the forced pressure rise in the enclosure. The arc voltage and consequently the power conversion in encapsulated arresters is higher than in the previously used blow-out arresters.

Apart from these thermal loads, the arrester is also subjected to heavy mechanical load due to the resulting pressure. These additional loads, which might be increased by the encapsulation, cannot be completely prevented due to the design and material of the arrester components, but can be reduced to an acceptable level by means of an adequate construction.

3 THEORETICAL CONSIDERATIONS ON A FULLY ENCAPSULATED LIGHTNING CURRENT ARRESTER

Let us denote the so called Joule integral as a function of time

$$JI(t) = \int_0^t I^2(\tau)\mathrm{d}\tau \qquad (1)$$

The theoretical considerations on the required follow current limitation of the lightning current arrester are based on the given input parameters:

- Max. continuous operating voltage $V_P = 255$ V AC.
- Prospective short-circuit current of the power supply system $I_{\mathrm{pros}} = 25$ kA.
- Let-through integral value $JI(t_D)$ be smaller than the melting integral value $JI(t_S)$ of a fuse NH 100 A gG.
- DIN rail mounted device with a width of max. 2 modules.

3.1 Follow Current Limitation

As is known, the velocity of the voltage increase and the value and stability of the arc voltage in the arc splitter chamber are important factors to limit the short-circuit current in a switching device or in an arrester with arc splitter chamber.

The velocity of the voltage increase depends on the time until the arc reaches the arc splitter chamber and the time until the arc is divided in the arc splitter chamber. The main influencing parameters are the distance between the point of arc formation and the arc splitter chamber as well as the arc velocity. The velocity is influenced by the forces acting on the arc, the geometry of the arc area and the materials used.

The arc voltage in the arc splitter chamber can be determined in the usual way by means of the number of partial arcs and the materials used. The influence of these materials, in particular in the arc splitter chamber, should ensure a stable arc behaviour during the entire load duration. The stability of the arc voltage in the chamber mainly depends on the arc behaviour. Arc back directly below the chamber or re-striking in the vicinity of the point of arc formation should be prevented.

For this reason, the first theoretical considerations should clarify which arc times and minimum arc voltages are required to achieve the desired current limitation under the given mains conditions.

These values and knowledge gained from switching devices indicated that the desired requirements are technically feasible.

During the (follow) current limitation process, the resulting arc energy heats the entire extinction system consisting of two electrodes, arc splitter plates of the arc splitter chamber, limiting side walls of the arc channel as well as the arrester enclosure and leads to a considerable pressure rise inside the arrester.

A simulation program was used to determine the required time characteristic of the arc voltage for the desired current limitation, in particular the rise time and the arc voltage value. A factor influencing the value of the let-through current and thus current limitation is the steepness of the current rise which depends among others on the time of the current formation (making angle α). The simulation was therefore carried out for different making angles (30°, 60° and 90°). In case of a spark gap the making angle corresponds to the arc ignition time following an overvoltage event referred to the phase angle of the low-voltage system. $t_0 = 0.3$ ms to 1 ms was chosen as time interval until the full arc voltage is reached and the arc voltage value was varied in a range from 300 V to 450 V.

The evaluation of the results was particularly based on the Joule integral $JI(t)$, (1). It was evident that the time until the maximum arc voltage is reached has the strongest influence on the $JI(t)$ value.

Another tested parameter is the maximum arc voltage which must be only a little bit above the peak value of the operating voltage for the desired current limitation. Figure 1 shows the described correlations in case of a making angle of 60°.

Figure 2 shows for example the simulated time characteristics at a making angle α of 60° in case of a rise time of $t_0 = 0.7$ ms until the constant arc voltage of $V_0 = 400$ V is reached. It becomes evident that the construction of the spark gap and the extinction system were supposed to increase the arc voltage to about 400 V within max. 0.7 ms (limit value 27 $\mathrm{kA^2s}$ in Fig. 1). After that, the arc voltage should be ideally constant and stable until the arc is extinguished. For this reason, 13 arc splitter plates are required in the arc splitter chamber to reach the required voltage of 400 V.

To assess the desired size, the thermal load on the plates was calculated, allowing an assessment of the volume of the arc splitter plates and the arc splitter chamber.

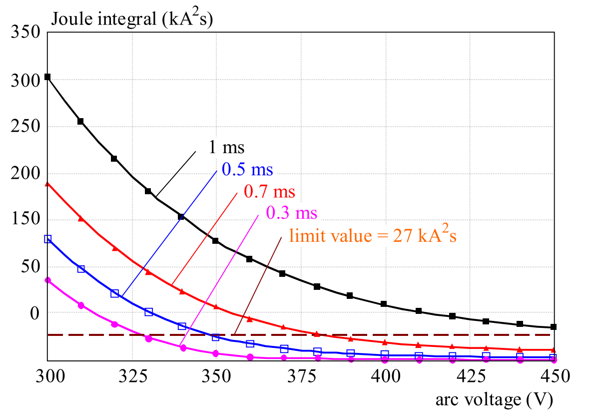


Fig. 1. Joule integral as a function of the arc voltage in case of different rise times (until the arc enters the chamber) at a making angle $\alpha = 60°$ ($V_p = 255$ V; $I_{\text{pros}} = 25$ kA, $\cos\varphi = 0.25$)

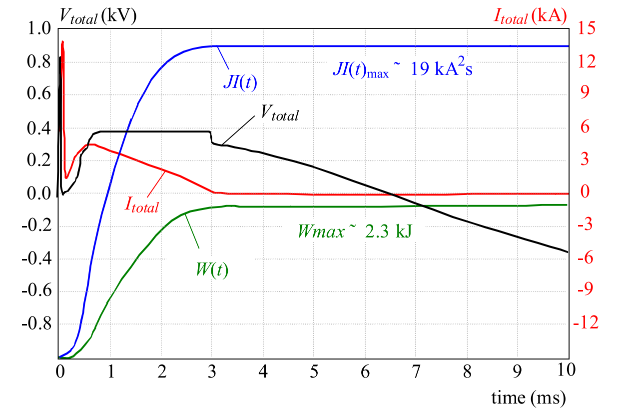


Fig. 2. Simulated time characteristics for a mains voltage of 255 V, prospective short-circuit current of 25 kA and $\cos\varphi = 0.25$

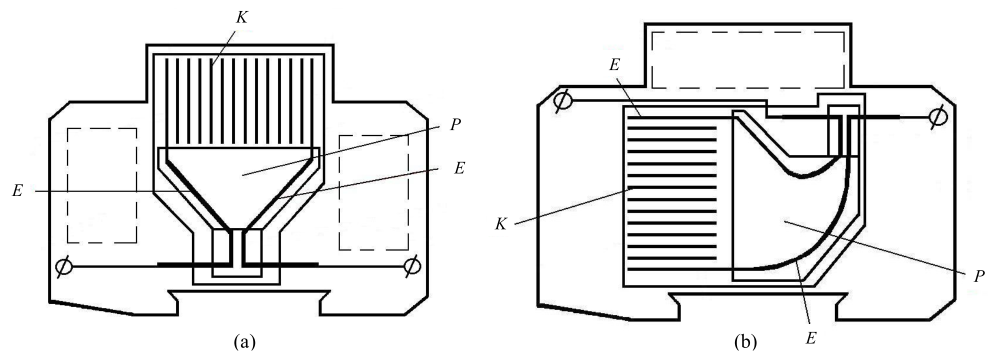


Fig. 3. Model with electrode arrangement: (a) – symmetrical, (b) – asymmetrical

3.2 Thermal Load on Splitter Chamber Plates

The required volume can be determined from the heating of the arc splitter plates due to the accumulation of the arc energy. For conventional switching devices it can be assumed that about 60 % to 70 % of the energy is converted in the arc splitter chamber and the contacts and about 20 % to 30 % in the tripping system [3, 4]. In case of an encapsulated lightning current arrester it must be assumed that the largest portion of the arc energy is accumulated in the arc splitter chamber. The following applies to the heating $\Delta\vartheta$ of the plates

$$\Delta\vartheta = \frac{W_k}{mc} = \frac{W_k}{V\rho c}\,. \tag{2}$$

W_k is the accumulated arc energy in the arc splitter chamber which corresponds to about 80 % of the arc energy W_0. The weight of the arc splitter plates m can be easily determined from the density ρ of the plate material used and the associated volume V. The specific heat capacity c is also mainly determined from the plate material used.

In case of an optimal function of the lightning current arrester during a follow current load an arc energy of about 2.3 kJ might occur so that the arc splitter chamber is loaded accordingly with approximately 1.8 kJ. In case of arc splitter plates with a slotted lead-in area and outer dimensions of 20mm × 24mm × 1mm the plates are heated by about 79 K according to (1).

Such a thermal load is uncritical for all common chamber materials and, as a matter of principle, can be exceeded twice to twice and a half.

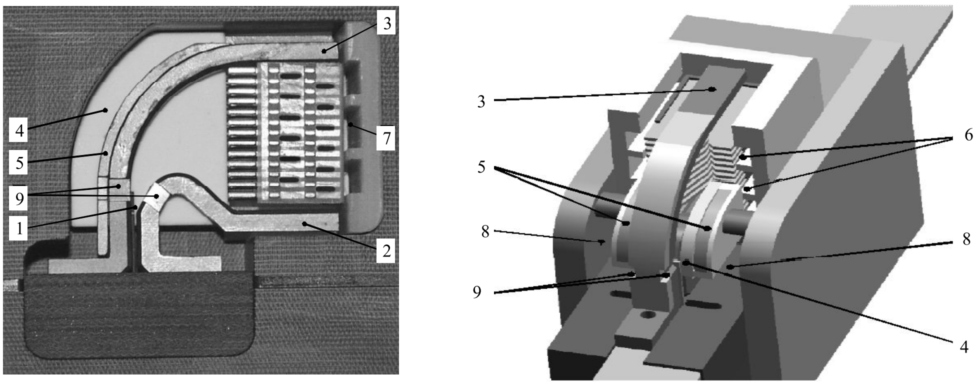
When loaded with lightning currents, the situation is more complicated since the current cannot be limited by the arcing chamber. The arc time is of great importance for such loads. It is to be expected that the maximum impulse current value is already exceeded before the arc enters the arcing chamber. It is difficult to assess in advance the energy conversion within the arcing chamber in the tail of the impulse. However, it can be expected that the chamber is loaded by a higher energy in particular in case of high lightning currents, for example 25 kA 10/350 μs.

3.3 Fundamental Considerations for a Sample Arrangement

Based on the geometric dimensions, the number of arc splitter plates required for current limitation as well as a common spacing between the arc splitter plates of approximately 1 mm, the following construction arrangements are possible in the desired volume of a DIN rail mounted device with 2 module width (36 mm). Fig. 3 shows two alternatives for a lightning current arrester with arc splitter chamber and symmetrical or asymmetrical electrode arrangement.

The goal of the experiments was to find a method to fully encapsulate the arrester.

The experimental preliminary tests were therefore carried out on simply sealed enclosures with an adequate in-



(a) (b)

Fig. 4. (a)– Horn arrester with arc splitter chamber for a nominal voltage of 255 V, (b) – Sectional view of a horn arrester with channels for internal gas circulation

ner volume. According to the above mentioned theoretical considerations, it is necessary for an optimal function of the arrester to ensure that the arc travels into the chamber with a high velocity. To achieve this high velocity, the arc should remain as short as possible at the point of formation and the velocity of the arc should be as high as possible. Moreover, it is useful if the path between the point of formation and the arc splitter chamber is as short as possible.

From extensive experience with covered switching devices it could be concluded that pressure waves significantly interfere with the movement of the arc and arc - back or re-striking might increasingly occur due to the accumulation of hot gases and the associated pressure increase.

If the arrangements shown in Fig. 3 are assessed under these aspects, the path in version 3a (symmetrical electrode arrangement) is shorter and similar electrodes or rails can be used. The arc formation area is directly below the entrance area in the arc splitter chamber, thus considerably increasing the risk of arc-back and re-striking. Furthermore, the required large distance between the two electrodes or rails with an opening angle of more than 60° is problematic for a fast and stable movement of the arc into the arc splitter chamber even if blow-out arresters are used.

Due to these two disadvantages of the arrangement according to Fig. 3a, which are even more negatively affected by the encapsulation, the sample arrangement is based on the construction shown in Fig. 3b. In this case, the probability of arc -back, which may occur already at the first attempt of the arc to enter the chamber, is considerably lower due to the spatial separation of the point of arc formation and the arc running area.

To solve the problem of fully encapsulated arresters, an internal gas circulation approach is pursued. This approach includes that the arc splitter chamber is covered a little bit and the gases released from the chamber travel through separate channels and are cooled. To be able to better assess the influence of the selected geometries and materials, the first tests with the sample devices were carried out in a test circuit with capacitor discharge and passive ignition of the spark gap. After optimizing the sample devices, they were tested in ac test circuits for comparison.

4 TEST RESULTS FOR DIFFERENT MAINS VOLTAGES

Figure 4 shows the basic design of the test sample. The arc is ignited at a defined point 1 between both divergent electrodes. The distance between the divergent electrodes is only significantly increased after the arc has traveled a certain path. This increase of the distance is achieved by changing the geometry of electrode 2. The other electrode 3 is curved. In the arc area the lateral chamber walls 4 and the curved electrode 3 consist of a ferromagnetic material 5. This measure additionally ensures that the arc travels to the entrance area of the arc splitter chamber.

The arc splitter chamber plates are mainly surrounded by an insulating material. The insulation of the chamber provides both side and front openings to release the gases from the chambers between the individual plates. The released gases are mostly passed through separate channels 6, 7 into side chambers 8 separated from the arc area for expansion. The gas recirculates into the arc area through recesses 9 in the electrodes. This recirculation takes place above the ignition area and below the greater electrode distance.

Figure 5 shows the current-voltage characteristics of the test set-up according to Fig. 4 with full encapsulation, but without internal gas circulation. The behaviour shown is similar to that of switching devices with a high degree of covering.

The travel behaviour is delayed and the arc division in the arc splitter chamber is not stable. Due to the reduction of the gas release (5b), for example by using burn-off-resistant materials in the arc ignition area, and of the associated low pressure build-up, only the behaviour with regard to the arc stability in the arc splitter chamber can be slightly improved.

Figures 6a and 6b show the current/voltage characteristics of a fully encapsulated arrester with closed internal gas circulation after optimizing the flow channels. Figure 6a shows the time characteristic in the test circuit with capacitor discharge and Fig. 6b in an ac circuit. The behaviour of the sample devices in the test circuit with capacitors and in the ac test circuit shows that encapsulated arresters are suitable for ac systems, ac systems with dc portions and pure dc systems.

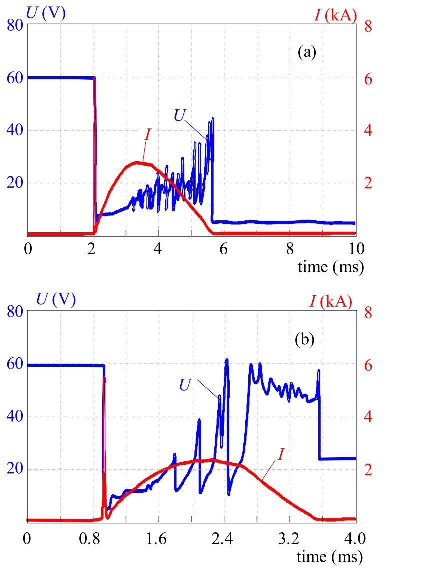


Fig. 5. Follow current limitation behaviour of an encapsulated arrester without gas circulation a) with gas release at $I_P = 9$ kA, b) without gas release at $I_P = 9$ kA

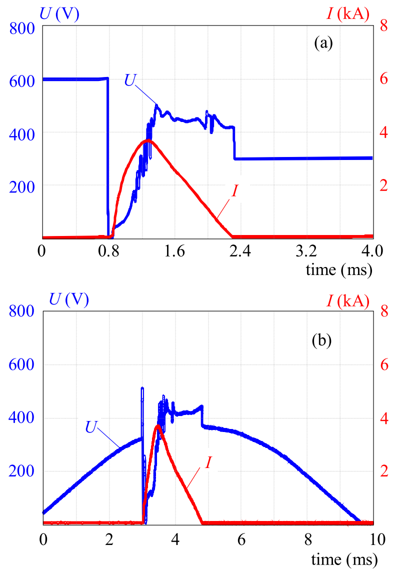


Fig. 6. Follow current limitation behaviour of an encapsulated arrester with gas circulation in a) capacitor test circuit, b) ac test circuit ($I_{\text{pros}} = 25$ kA)

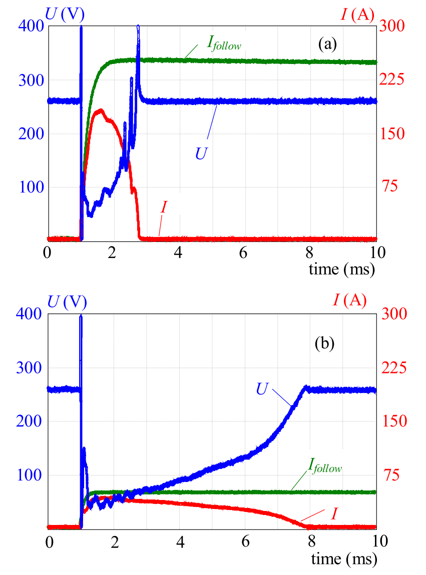


Fig. 7. Arc extinction at different mains voltage and time constants: (a) – 250 A, ≈ 0.2 ms, (b)– 50 A 255 V, ≈ 0.1 ms

Table 1. Current limitation and arc values

Making angle α (°)	Mains voltage V_P (V)	Prospective short-circuit current I_{pros} (kA)	Let-through current I_D (kA)	Specific let-through energy I_D^t (kA²s)	Arc time t_{arc} (ms)	Average arc velocity v_{arc} (m/s)	Average arc voltage V_{arc} (V)
90	255	1.0	0.72	0.83	1.87	25.1	289
	255	4.0	1.52	3.14	0.66	71.2	376
	255	12.5	2.95	7.69	0.57	82.5	437
	255	25.0	3.78	9.09	0.37	127.0	428
210	255	1.0	0.74	1.11	2.44	19.3	344
	255	4.0	1.13	1.89	0.94	50.0	360
	255	12.5	1.63	2.37	0.78	60.2	364
	255	25.0	2.24	3.04	0.59	79.7	345

Figure 7 shows the load on the arrangement with low direct currents at a voltage of 255 V. The time required by the arc to travel into the arcing chamber of the arrester is ensured even in case of very low direct currents without additional magnetic fields.

This ensures safe extinction of the currents in the arcing chamber (at 250 A) or already before the arc enters the arcing chamber (at 50 A).

In this arrangement no materials with additional gas release for cooling the arc or additional pressure build-up are used. In case of alternative dimensioning of the circulation channels with extensive cooling and thus expansion of the gases, however, gas-emitting substances can be additionally used for example to support the initial movement or to increase the arc voltage. The additional effort for other materials and the volume required for the desired parameters always have to be weighed against the benefits.

The experiments confirmed that the full encapsulation is the biggest problem for achieving the required arc voltage according to the simulation results. In addition, the materials of the sub-systems considerably influenced the arc mobility and the interaction of the materials with the arc.

The solution with optimized gas circulation in the extinction system presented above allowed to achieve both a high arc velocity to the arc splitter chamber and a high and stable arc voltage. The arc-backs directly at the entrance point into the arc splitter chamber could be limited to a minimum in case of follow currents. Table 1 shows important measured values which could be achieved by means of the sample devices for different ac voltages and prospective currents. It is evident that the values of the let-through currents and the specific let-through energy (Joule integral), which can be used to assess the follow current limitation, are very low in a wide current range.

Since the behaviour of an arrester with regard to the thermal and dynamic load in case of lightning impulse currents can only be assessed considering the specific device construction and the material properties [5], this considerable effort for the sample arrangements was not jus-

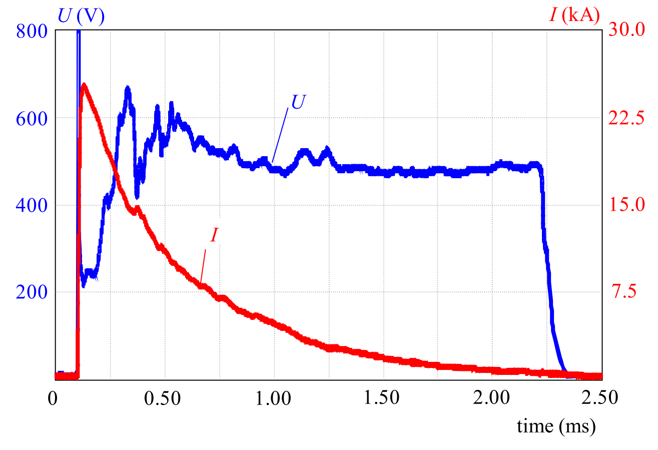


Fig. 8. Arc voltage in case of a lightning impulse current of 25 kA – 10/350 μs

tified. For this reason, tests on the general suitability of the sample arrangement were only based on experiments.

Figure 8 shows the behaviour of a sample device according to Fig.4 in case of a lightning impulse load with 25 kA of 10/350 μs wave form. Even though the energy conversion (approximately 4.3 kJ) of the arc in the arcing chamber is high after the arc entered the chamber, the energy load and the associated temperature rise ($\Delta\vartheta \approx 177$ K) of the plates in the arc splitter chamber can be controlled without major damage. The normal function of the lightning current arrester following such a load is still ensured.

5 CONCLUSIONS

Lightning current arresters in low-voltage systems do not only have to discharge lightning currents, but also limit and extinguish mains follow currents. In encapsulated lightning current arresters, which are designed as horn arresters with arc splitter chamber and do not blow off hot arc gases in case of lightning and follow current load, specific measures have to be taken to cope with the load in case of lightning impulse currents and to ensure a high follow current extinguishing capability.

An effective entrance and a stable behaviour of the follow current arc in the arc splitter chamber is achieved by optimally venting the arc splitter chamber, cooling hot gases in expansion chambers and closed internal gas circulation through flow channels in the arrester. Thus, the encapsulated lightning current horn arrester ensures high current limitation, thus preventing mains interference or power failure.

It could be concluded from theoretical considerations and it could be shown in experiments that the construction of the compact horn arrester is capable of controlling lightning impulse currents up to 25 kA and limit and extinguish follow currents up to 25 kA at a mains voltage of 255 V.

References

[1] RÜTHER, T. : Experimental Test on the Arc Division on Arc Splitter Plates, Dissertation TU Braunschweig, 2007.

[2] EN 61643-11, 05/2002 edition, Low-Voltage Surge Protective Devices Part 11: Surge Protective Devices Connected to Low-Voltage Power Systems-Requirements and Tests.

[3] HÜTTNER, L. : Proc. of the VIIIth Symposium on Physics of Switching Arc, 1988, pp. 97–105.

[4] JURČACKO, L. : 9th Symposium on Physics of Switching Arc, 1989, pp. 23–30.

[5] POSPIECH, J. : New Principle for Lightning Current Arresters in Low-Voltage Systems, Dissertation, TU Ilmenau, 2001.

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