A HV VARISTOR ASSISTED FUSE

A.D. Wolny and A.D. Stokes

Results of investigations on fuse-to-varistor current commutation has been presented, indicating that a significant reduction in the energy dissipated during a fault current breaking by the fuse can be achieved if the support of a parallel varistor is provided. In the focus of interest are expulsion fuses, which are cheaper and better suited for high voltage operation, because of their possible full range characteristic. The varistor assistance can increase almost infinitely fuse breaking capacity, reduce significantly gas expulsion, permitting even a closed fuse design, and limiting fire hazard. Basic features required for a fuse design to operate with the assistance of a varistor has been discussed for both low and high current faults. Although voltages as high as 1 kV/cm can be generated by fuses with small diameter capillary confinement, in most practical applications, the authors used a half of that value.

1. Introduction

The current interruption supported by an external energy absorber displays many advantages. To the most important belong: the dramatic reduction in the energy dissipated in current breaking devices, a higher current breaking capacity and capability of current limitation with devices which, typically, interrupt currents at current zero while operating independently. Such effects, Fig. 1, can be acquired by means of, eg., electrical arc-to-varistor current commutation. The idea works in both AC and DC circuits.

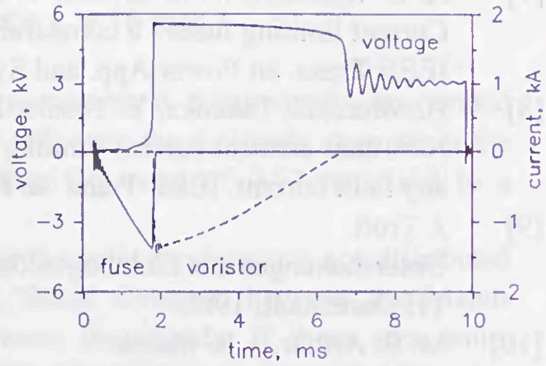

Fig. 1. Expulsion fuse-to-6-kV varistor current commutation in an oscillatory test-set. Prospective current I_p=2.2 kA r.m.s.

The condition of current commutation is a high arcing voltage generation, exceeding that of varistor voltage. Hence, the best suited arcing device for such an operation seams to be a fuse which, typically, produces a very high arc ignition peak voltage in a very short time. It should be underlined that the fuse ability to create the required high arcing voltage in a few tens of microseconds is very beneficial, because this way the precommutation arcing period, and the arc dissipated energy, can be significantly reduced. Having analysed the fuse-to-varistor current commutation process, the authors showed that varistor assisted fuses possess almost unlimited current breaking capacity [1].

Compared features of a variety of fuses, one concludes that expulsion fuses are better suited than other types to be applied to fuse-varistor arrangements. They perform better under low overcurrent conditions than sand fuses, and their operations are cheaper. There is no need to bother about relatively low breaking capacity of expulsion fuses if one expects an efficient varistor assistance while clearing high current faults. Arc ignition voltage peaks of sand-filled and expulsion fuses are comparable if diameters of ablative confinements are small enough [3]. Previous reports of the authors [2, 3, 4, 5] show that expulsion fuses with very close capillary enclosures are able to produce not only high, but also steadily rising voltages. For all these reasons, attention has been focused on expulsion fuses.

In practice, there is no need to commutate currents from an expulsion fuse to a varistor at low overcurrents. The current limitation and arc energy reduction are not attractive under such conditions. Therefore, current commutation has been only analysed, and tested for high current faults. Nevertheless, the fuse features associated with the varistor support during the operation do influence the fuse behaviour while breaking low currents and such a problem has been also examined.

2. Current commutation process

The current transfer from an arc to a varistor depends on special arc features. First of all, the arc ***u-i*** characteristic should be a positive slope curve. However, this is not enough. Such a curve could also lead to a partition of current between the arc and varistor. To commutate the current, additionally, two other conditions have to be met [5]:

- the main circuit current must not reduce significantly due to the rising arcing voltage;

- the rate of energy deposited in the arc limited by the varistor voltage, must not balance the rate of dissipation and absorption of arc energy for any arc current.

The first condition indicates that the system magnetic field energy is high enough to force the current through the varistor, and the second implies that the arc internal energy has to be diminished, causing plasma deionisation. If a fuse is applied as the arcing device, the disintegration of fuse element during the arc ignition process guaranties a high rate of absorption of energy by the fuse element disintegration. Unlike in the process of current interruption, the success of current commutation is not connected with the competition between TRV and the rise in dielectric strength. In the latter case the arc and post arc column are intensely stressed by the varistor voltage.

Fuse-to-varistor current commutation starts after the fuse arcing voltage has exceeded that of varistor, and before the arc ignition peak voltage. The latter event occurs towards the end of fuse element segmentation process, when the fuse current path, is formed by the maximum number of liquefied metallic segments of the disrupted fuse element [3]. Judging from the energy deposited in the fuse up to that instant [6], the total length of plasma segments connecting metallic segments must be considerably smaller than the length of fuse element. To create an uniform arc column a sizeable amount of fuse element metal must still be vaporised and removed. Therefore, one can imagine that the current commutation process, starting clearly before the arc ignition voltage peak, must be forced by the continued fuse element rupturing and disintegration at an almost constant voltage defined by the varistor [5]. At that time the heat dissipated by the arc cannot be very high due to still a low arc plasma temperature and moderate length of plasma segments.

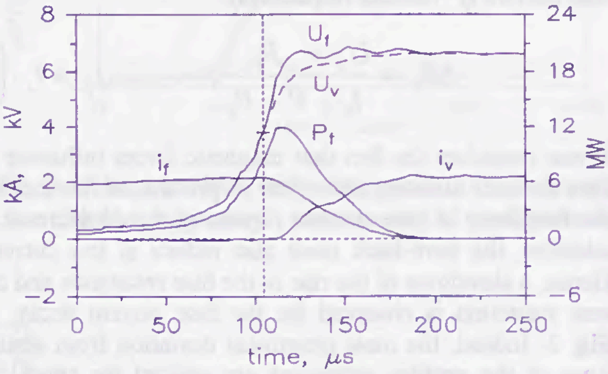

Fig. 2. Expulsion fuse-to-varistor current commutation. Copper fuse element, 0.36-mm ∅, inserted into nylon confinement, 2-mm ∅, and 6-kV varistor were used.

A model process of fuse-to-varistor current commutation is illustrated in **Fig. 2**, in which records of currents, voltages and power are presented for an arrangement consisted in an expulsion fuse and 6-kV varistor, operating in a 6-kV oscillatory test-set. The varistor voltage U_v was calculated based on the varistor ***u-i*** characteristic, inductance L of the fuse-varistor loop, and current records. The fuse current i_f is forced to zero in a time slightly exceeding that of the voltage rise, the fuse voltage U_f is markedly higher than that of varistor U_v during the commutation process, and the temporal function of fuse power P_f is approximately an isosceles triangle-shaped curve. The total fuse arcing time is less than 200 μs. It is noticeable that the sum of varistor and fuse currents ($i_f + i_v$) remains almost constant during the commutation process.

To understand better these observations a short examination of the simplified circuit of fuse-to-varistor commutation, presented in **Fig. 3** helps, where V is the ideal varistor, R is the sum of the varistor resistance responsible for the increase in varistor voltage U_v due to the current rise and remaining loop resistance, i_s is the current forced by the system, i_v is the varistor current. The current commutation process starts when the fuse voltage $U_f > U_v$, because the positive difference of voltages ($U_f - U_v$) produces a positive varistor current time derivative di_v/dt implying an increase in i_v and reduction in i_f, since

$$i_f = (i_s - i_v). \qquad (1)$$

To enforce a rapid current commutation, ($U_f - U_v$) must be positive and high. The initial, approximately isosceles triangular shape of the fuse power curve P_f, Fig. 2, is typical for a smooth commutation processes. It demonstrates similar rates of change of fuse deposited power in arc ignition and commutation periods. However, the signs of changes are opposite.

This assumption can be examined closer in Fig. 4 presenting linearised and normalised profiles of fuse and varistor currents and voltages as well as the fuse power P_f. With $\dot{i}_f = 1$ constant, $\dot{U}_f$ and $\dot{P}_f$ increase linearly, following line AB. With the absence of varistor V, $\dot{U}_f$ and $\dot{P}_f$ continue to rise at unchanged rate and constant current between points B and D'. The power growth in the interval ($t_d - t_m$) is P_1, which is equivalent to an increase in the fuse resistance $\Delta R = P_1 / i_s^2$. In accordance with the analysis given in [3], this effect is mainly due to the rupturing of fuse element.

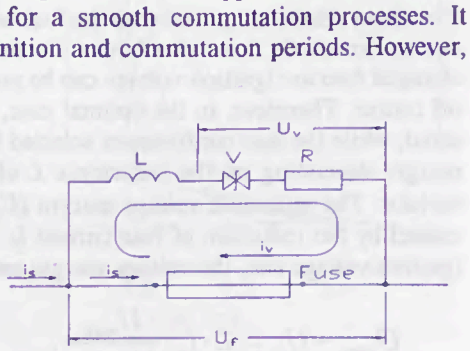

Fig. 3. Fuse-to-varistor current commutation circuit.

In the case of current commutation, the rupturing has to be continued, however, at the constant voltage U_v instead of constant current i_s. One can imagine that in both cases a similar portion of energy is needed to create each break, which is connected with the decomposition of a portion of volume of the fuse element. Hence, assumed that the frequency of rupturing depends, first of all, on the energy actually deposited in the fuse element, which does not change abruptly, the energy used for the disintegration of fuse element over the same interval of time $(t_d - t_m)$ for both processes, e.g., the fuse arc ignition and current commutation should be initially similar, $P_1 \approx P_2$. This reasoning leads to the conclusion that in both cases a similar increase in the resistance of fuse current path must be expected. Therefore, during the current commutation interval $(t_d - t_m)$, the fuse resistance ΔR_c increases, and fuse current i_f reduces respectively.

$$\Delta R_c = \frac{U_v}{i_s} \cdot \frac{P_2}{P - P_2}, \qquad i_f = i_s \cdot \left(1 - \frac{P_2}{P}\right), \quad \text{where} \quad P = U_v \cdot i_s \tag{2}$$

If one considers the fact that magnetic forces influence the fuse element disintegration then in practice at low currents the frequency of fuse element rupturing should decrease. In addition, the burn-back must also reduce at low currents. Hence, a slowdown of the rise in the fuse resistance and current reduction is observed for the fuse current decay, see Fig. 2. Indeed, the most prominent deviation from straight lines of the profiles examined are noticed for small fuse currents. Therefore, the commutation time t_c and energy W_c defined in Fig. 4 should be considered minimum. A simplified calculation of the latter parameters is easy to perform followed Fig. 4 and applying the average rate of rise of the fuse arc ignition voltage given by the quotient of ignition peak voltage U_{max} and time of its creation t_{ign}.

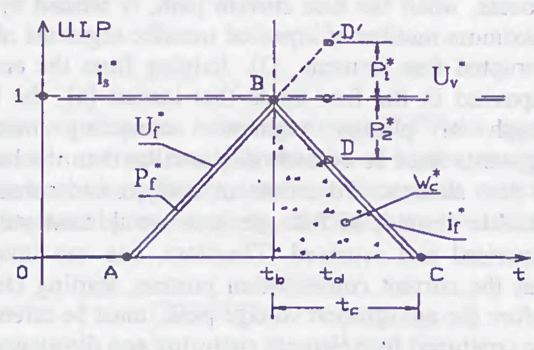

Fig. 4. Linearised and normalised U_f^*, i_f^*, P_f^* curves

$$t_c = \frac{U_v}{U_{\max}} t_{ign}, \qquad W_c = 0.5 \cdot i_s \frac{U_v^2}{U_{\max}} t_{ign} \tag{3}$$

Typically, for properly defined length of the fuse element, the fuse arc energy of a varistor assisted fuse need not be much higher than the fuse arc ignition energy. This implies that a fuse operating under such conditions dissipates no more than a few percent of the arcing energy of a stand alone fuse. Therefore, a dramatic increase in the current breaking capacity is observed after application of the parallel varistor.

3. Basic features of fuses for the fuse-varistor assembly

There is no doubt that the fuse current cannot be totally commutated to the varistor until such a part of the fuse element has been disintegrated that the gap created is able to withstand the varistor voltage. This gap may be taken as a criterion of the minimum length l_{min} of fuse element. However, it is worth bearing in mind that the arc ignition peak voltage U_{max}, which must exceed the varistor voltage U_v, also depends on the fuse element length l. Therefore, in practice, both l_{min} and l connected with U_{max} have to be taken into consideration, and under special conditions only, both of them are similar. This reasoning leads to the conclusion that an optimal fuse length and design should exist.

Examined relationships between the fuse arc ignition voltage peak, confinement diameter, and fuse element length, one can conclude that these factors are strictly interconnected [3]. Thus, applying a shorter fuse element, the unchanged fuse arc ignition voltage can be produced just with a smaller confinement diameter, with some limitations, off course. Therefore, in the optimal case, the fuse element length should be founded on the minimum gap withstand, while the fuse confinement selected this way that U_{max} exceeds the varistor voltage U_v with an indispensable margin depending on the inductance L of the commutation loop consisted in connections between the fuse and varistor. The minimum voltage margin $(U_{max} - U_v)$ should exceed the inductive voltage drop $L \cdot di_v/dt$ in the loop caused by the reduction of fuse current i_f. For the fastest reduction, with the slope corresponding to the fuse arc ignition voltage rise, the voltage margin can be evaluated from the following expression:

$$U_{\max} - U_v = L \cdot i_s \cdot \frac{U_{\max}}{U_v \cdot t_{ign}}, \quad \text{or} \quad \frac{U_{\max}}{U_v} = \frac{1}{1 - \dfrac{T_c}{t_{ign}}}, \quad \text{where} \quad \mathrm{T_c} = \frac{L \cdot i_s}{U_v \cdot t_{ign}} \tag{4}$$

Equation (3) suggests that the inductance L of commutation loop should be as small as possible. However, an analysis of the fuse arc ignition process shows a similar behaviour of a fuse and a capacitor in electric circuits under dynamic conditions [5]. Therefore, presence of a certain loop inductance L is beneficial, since the energy stored in magnetic field accelerates the current zero in RLC circuits for currents significantly reduced. Oscillatory, near critical response of circuit is welcomed, hence, the beneficial loop inductance L can be calculated for the loop resistance R_l taking also into consideration the varistor u-i characteristic, and a capacitance C_a defined by the ratio of the system current i_s and the average rate of rise of the fuse arc ignition voltage, substituted for the fuse ignition arc. For such a model the time constant T_c, defined in (4) can be transformed to the following expression:

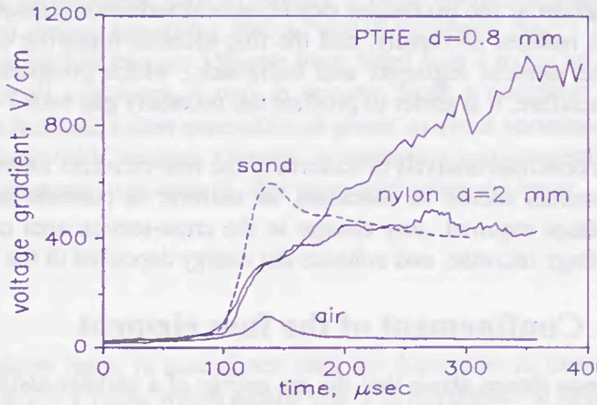

Fig. 5. Voltage gradient of the fuse arc ignition for copper fuse element, 0.36-mm ∅, and a variety of confinements

$$T_c = \frac{4R_l^2 \cdot i_s}{U_{\max} \cdot U_v} \tag{5}$$

This definition permits, followed (3), to calculate the fuse arc peak voltage U_{max} required, which enables to establish the fuse element length if the maximum voltage gradient for the suggested fuse design can be assumed. The authors found that, although a voltage gradient as high as 1 kV/cm can be generated by expulsion fuses with capillary confinements, in such a case, the time required is long, due to a slowdown in the rate of voltage rise if higher than approximately 300 V/cm [3]. The level of 600 V/cm can be achieved with sand filled fuses. Therefore, for practical applications the gradient of 0.4÷0.6 kV/cm seems to be the most typical. In Fig. 5, profiles of voltage gradients of the fuse arc ignition, recorded by the authors, are shown for the prospective current 2.2 kA r.m.s. and a variety of confinements.

It is important to notice that a very long fuse element may be also disadvantages from the point of view of efficiency in current commutation. Since, the rate of rise of arc ignition voltage, and the initial current reduction during the commutation process depend on the length of fuse element, one can expect that the longer the fuse element the shorter the commutation time and the lower the energy involved. However, a very fast fuse voltage buildup can cause a rapid fuse current reduction to a certain point only because the rupturing will be stopped and burn-back become less effective due to the low current value. At that moment the total gap in the fuse element can still be too short to withstand the varistor voltage. In such a case, a lingering current can be observed, enforced by the varistor voltage, if the dissipation of arc energy is sufficient. If not, the current transfer is reversed and the fuse takes again the whole of the current over. Under beneficial conditions the reduced current may flow until the gap is extended enough, by the burn-back, to conclude successfully the commutation, which takes, however, a long time.

To support these assumptions, the current of a fuse, 950 mm in length connected in parallel with a varistor composed of a variable number of 6-kV blocks is presented in Fig. 6, for a commutation period. The number of blocks varied from 1 to 6. The prospective U_{max} and the rate of rise of the fuse arc voltage were equal in all cases. The commutation loop inductance was approximately of 12 μH, due to long connections to the current measuring shunt. For a low number of blocks the initial rate of current reduction is the same for all curves, in accordance with the discussion in the former sections. In such a case, the fuse current is suppressed rapidly to a low value, and persists over a long time, until the necessary gap is created by the deformation of liquefied segments and burn-back. When the number of blocks increases, the varistor voltage rises and the voltage difference (U_{max} - U_v) becomes too low to balance the inductive voltage drop

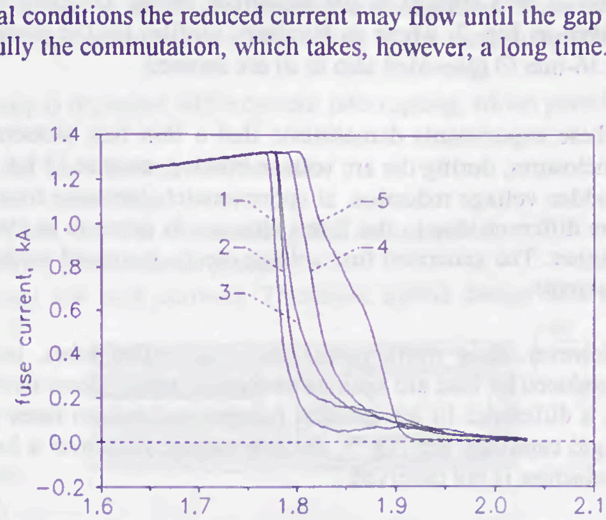

Fig. 6. Commutation fuse current for a variable number of varistor blocks (1÷6 denote the number of blocks).

$L{\cdot}di_v/dt$ at the maximum rate of current reduction. Hence, di_v/dt must decrease. In the latter case, the current is not reduced so rapidly, and the fuse element rupturing can be accompanied by the deformation of the liquefied fuse element segments and burn-back., which produces longer gaps at currents reduced to the same degree. Therefore, it is easier to produce the necessary gap with 1-block varistor than with 6 blocks.

To conclude analysis of features of the fuse elements for varistor supported fuses, it is worth noticing that such fuse elements should be notchless, as uniform as possible to secure a fast generation of the very high arc ignition voltage required. Any change in the cross-section area must diminish the frequency of rupturing, slow down the voltage increase, and enhance the energy deposited in the fuse. The voltage peak would also be lower.

4. Confinement of the fuse element

It was shown above that the arc energy of a varistor assisted fuse is relatively low. On the other hand the pressure must be very high to generate high fuse arc ignition voltages [4]. These factors exercise opposite effects on the fuse design. Low energy means a light, material saving construction, and high pressures require, even if acting only a short time, strong, resistant enclosures.

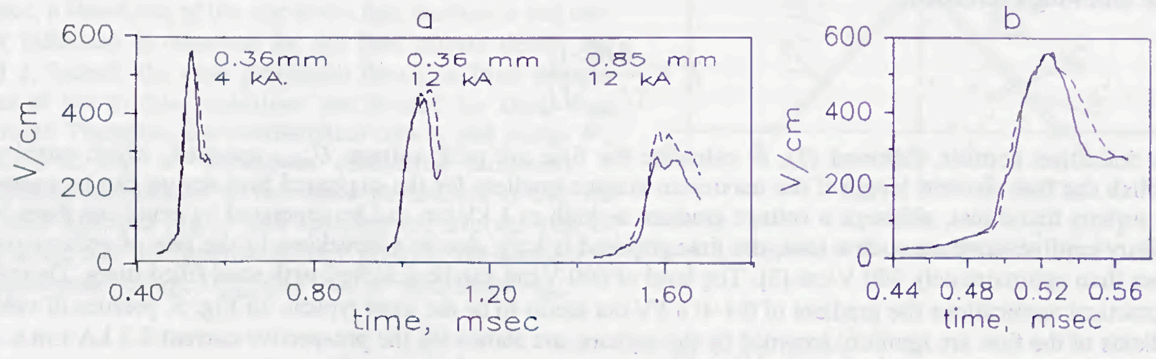

Fig. 7. Fuse arc ignition voltage in simple (continuous line) and reinforced (broken line) confinements. Fuse element diameters and prospective currents (r.m.s.) are provided.

To find the answer to the question what should be the characteristic like of the enclosure of fuse element of the varistor assisted fuse, fuse voltages were recorded during arc ignitions, for copper fuse elements inserted into simple or reinforced confinements. The simple enclosure consisted in a PTFE tube, 1-mm ∅, squeezed into a nylon tube, 2 mm in the inner diameter. Walls of the latter tube were 0.5 mm thick. The enclosure with the fuse element inside was inserted into ABB drop-out carrier, with the bore of 12.8 mm in diameter. An additional nylon tube, 3-mm ∅, was applied in the reinforced model. Differences in the arc voltage profiles were examined. Results are given in **Fig. 7,** where in ***b*** voltage profiles for the prospective current of 4 kA r.m.s. and copper fuse element, 0.36-mm ∅ (provided also in ***a***) are zoomed.

These experiments demonstrate that a thin fuse element behaves similarly in the simple and reinforced nylon enclosures, during the arc voltage buildup, even at 12 kA. The confinement starts to rupture, which is marked by a sudden voltage reduction, at approximately the same time for both models. However, rates of the voltage decrease are different, due to the faster changes in pressure in the simple model, where the degree of tube destruction is higher. The generated fuse voltage can be increased markedly by reinforced confinement, for thick wires and high currents.

However, it is worth noting that thin-walled tubes, both simple and reinforced, expand due to the pressure produced by fuse arc ignition processes, which slows down further pressure and voltage increase. Therefore, there is a difference in arc ignition parameters between fuses with rigid and plastic tubing confinements. In case of a rigid capillary, see Fig. 5, the fuse voltage rises over a long period and acquires a high level. The sudden voltage reduction is not observed.

The way the arc affects enclosures also is different. Nylon tubes inserted in large carriers break, typically, at a number of points. They fail to be torn completely to pieces. Later, they are melted or destroyed in a higher degree by arcs burning over significant part of the halfperiod. The authors made these observations compared a great number of enclosures after current commutation to a varistor and a full halfperiod operation.

The low energy deposited in varistor assisted fuse, during its operation, fails to produce a large volume of gases, even in organic confinements. Therefore, it is possible to design something like a "sealed expulsion fuse". To check this idea, experiments have been carried out with a rigid fuse carrier, 150 mm long, lined with a nylon tube, 2 mm in inner diameter, and closed at both ends with small containers, 6 cm^3 in volume. Such a container is presented in **Fig. 8**. Small bores, 2-mm ∅, were drilled to facilitate a slow evacuation of gases, to avoid permanent high pressure. The fuse was connected in parallel to 1-block, 6-kV varistor. Current commutation was successful for currents ranging from 2.2 kA to 8 kA and copper fuse elements, 0.36-mm ∅. The fuse itself remained intact.

5. Interruption of overload currents

In both types of fuses, i.e. sand filled and capillary expulsion fuses, in accordance with the discussion in former sections, the arc ignition voltage gradient can be as high as 0.5 kV/cm, which means that it is impossible to apply short fuse elements, for operation under typical distribution conditions, especially if one takes into consideration the indispensable margin between the system and varistor voltages. Followed the discussion in [1], this margin should be at least 50% of the operating voltage to avoid unnecessary bulky varistors. Hence, e.g. for 24 kV, even under comfortable conditions, i.e. for earthed neutral system, the fuse element cannot be shorter than 0.6 m. For systems with isolated neutral a further increase in length is necessary. If cheap construction is used, with a plastic tubing enclosure placed in a large carrier, as described above, the fuse element should be twice as long. This way, the fuse element length of a varistor assisted fuse can be comparable to that of a regular sand fuse. However, in case of capillary expulsion fuses, there still is a difference consisting in the possibility to extend the arc mechanically, to accelerate voltage buildup while interrupting very low currents.

Moreover, taking into consideration the above mentioned condition that the fuse element should be uniform to generate rapidly a high voltage, it becomes clear that shaping low current ***t-i*** characteristic is not a simple task and the varistor assisted fuse is better suited for breaking short circuit than overload currents. To meet requirements of standards, the most reasonable solution seems to be a two-part hybrid design in which overload currents will be broken by a short, expulsion type segment.

To learn the behaviour of varistor assisted fuse at low currents the authors compared the process of interruption of 60 A with a 0.95 m long, capillary expulsion fuse with copper fuse element, 0.57-mm ∅, without any mechanical arc extension, with and without the varistor assistance. In the former case, a very high overvoltage was generated, due to the long confinement. In the latter, the voltage was limited, and after a long arcing time the fuse current was eventually commutated.

6. Conclusions

- Fuse-to-varistor current commutation is enforced by the process of the fuse element disintegration. Therefore, the rate of fuse current reduction during commutation is connected with the rate of rise of the fuse arc ignition voltage.
- In the varistor assisted fuse, a few percent of energy only is deposited while current interrupting, which permits to use material-saving fuse constructions.
- Small diameter, simple plastic tubing can be used for the fuse element confinements.
- Closed expulsion type fuses are practical for fuse-varistor assemblies.
- With available fuse ignition voltage gradient of 0.5 kV/cm, the fuse element length is considerable.
- Too long fuse elements can adversely influence the current commutation process.
- The varistor assisted fuse is not suited well to interrupt low fault currents. Therefore, hybrid design with an overcurrent part can be recommended.

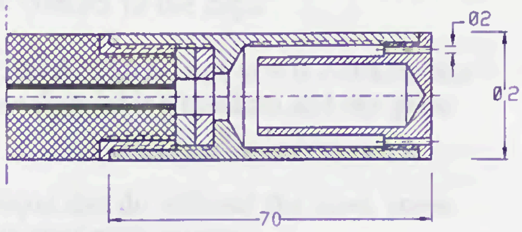

Fig. 8. Gas container of the closed, varistor assisted expulsion fuse

7. References

1. Wolny A., Stokes A.D., Kacprzak B.: High voltage fuse behaviour with varistor commutation. Proc. IEE 1994, vol. 141, No.1, p. 33.
2. Wolny A., Stokes A.D.: Varistor assisted fuse current breaking. Int. Symp. on Switching Arc Phenomena, Łódź, 1993, p. 245.

3. Wolny A., Stokes A.D.: Electrical arc ignition in narrow slots: high voltage generation. Proc. IEE 1994, vol. 141, No. 4, p. 263.
4. Wolny A., Stokes A.D.: Ignition of an electrical arc in a capillary: arc parameters in the initial period. Proc. IEE 1994, vol. 141, No. 5, p. 480.
5. Wolny A.: Fuse-to-varistor current commutation. Zeszyty Naukowe Politechniki Gdańskiej "ELEKTRYKA" 1994, No. 76. Wydawnictwo Politechniki Gdańskiej.
6. Vermij L.: The voltage across a fuse during the current interruption process. IEEE Trans. 1980, vol. PS-8, No. 4, p. 460.
7. Kul'gavchuk V.M., Novoskol'tseva G.A.: X-ray study of kinetics of heating and evaporation of exploding wires. Sov. Phys., Techn. Phys. 1966 vol. 11, No. 3, p. 406.