Dielectric strength of the ultra-short fuse

Borys Semenowicz[(1)], **Roman Partyka**[(1)]

Gdansk University of Technology[(1)], Własna Strzecha 18A Str. 80-952 Gdansk,
bsemen@ely.pg.gda.pl [(1)], rpartyk@ely.pg.gda.pl [(2)]

Abstract: The assembly of a very short fuse and the semiconductor switch connected in parallel costitute fast acting, contactless hybrid current limiter whose characteristics strongly depend on features of the short fuse. Both static voltage withstand and the recovery of dielectric strength of the short fuse co-operating with the semiconductor device are discussed. The dielectric strength of the gap between fuse contacts defines the length of the fuse element, and the recovery time dictates the time of current interception by the semiconductor device. It has been shown that the fuse element length of about 1 mm is sufficient for LV current limiters and an optimum time of current interception by the semiconductor device exists.

Keywords: short electric fuse, short gap dielectric strength, fuse recovery voltage, hybrid current limiter

1. Introduction

Hybrid short circuit current breaking and limiting devices were first proposed several years ago by Collart and Pellichero [1]. They were relatively slow due to the inertia of the operating mechanism. Czucha and Żyborski [2] sped up the operation by the application of a switch, whose contacts were simply bent by an impulse of strong magnetic field. Recently, Wolny [3,4] developed the idea of a fuse substitution for the contact switch in the hybrid assembly, to avoid problems with the operating mechanism and to reduce costs and dimensions of the current limiter by removal of the expensive equipment indispensable for generation of strong magnetic field.

The latter hybrid assembly has been called contactless hybrid current limiter (CHCL). There are the fuse features, which decide CHCL characteristics. After the fuse element has been completely decomposed, the static voltage strength of the gap between fuse electrodes, defines the permissible length of the fuse element, and consequently the intensity of axial cooling effect. The gap between fuse electrodes must not be shorter than that withstanding the required testing voltage after the decomposition of the fuse element.

The time of current interception by the semiconductor device is connected with the recovery process of the fuse dielectric strength. This time affects the level of current limitation. The longer the semiconductor device passes the current through, the higher the cut off current is.

Two factors influence the semiconductor let through time: the speed of the fuse element decomposition after the arc ignition, and the deionisation of the created gap. The former defines the optimum turn-on time of the parallel semiconductor device, starting the current transfer, and the latter – the moment of turn-off of the semiconductor device transferring the current to the energy absorber (MOV) forcing the current to zero. Below, both factors are discussed.

2. Fuse static withstood voltage

A short fuse is also applied in the main circuit of the two-path fuse. In CHCL and in the former case the practical lengths of fuse elements are comparable, as the axial heat conduction cooling effect in both cases must be dominant. Nevertheless, the shapes of electrodes differ, as in the two-path fuse a dielectric barrier has to be inserted into the gap to enhance the arcing voltage and dielectric strength. It is easier to model electric field in the short fuse designed for CHCL.

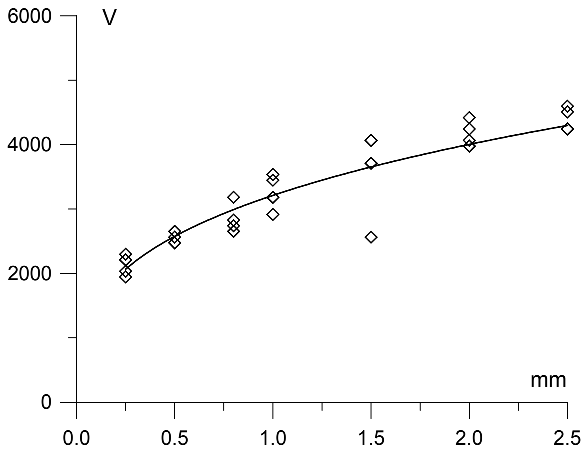

Fig. 1 Dielectric strength of the air gap between copper flat electrodes with sharp edges, vs. distance, modelling a short fuse for two-path fuse assembly [5]

Extensive, research on the dielectric strength of a short fuse for the two-path fuse assembly was carried out by Sztenc [5]. He used air and compressed gases and changed the fuse gap in the range of 0.25÷2.5 mm. His model consisted in flat electrodes with sharp edges perpendicularly joined with flat bus-bars. Based on private connections selected results of his measurements are shown in Fig. 1. It is noticeable that in the air the withstood voltage rises slower than proportionally as the fuse gap, and a 1-mm gap is sufficient for LV applications.

Results of tests carried out at compressed air show an exponential dielectric strength increase as the pressure, Fig. 2 [5].

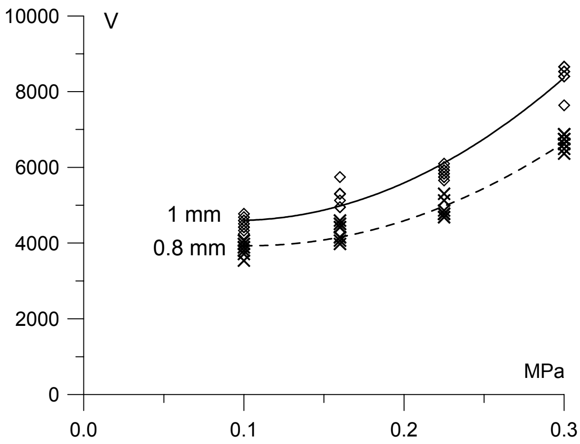

Fig. 2 Dielectric strength of the air gap between copper flat electrodes with sharp edges vs. pressure, modelling a short fuse for two-path fuse assembly [5]

The tests by Sztenc [5] were carried out with a set of clean electrodes. No marks of erosion caused by the arc were considered. To find out how far his results differ from those expected for a short fuse designed for CHCL operating in practical conditions, the authors performed additional tests. The short fuse with 0.5-mm strip fuse element after the operation withstood 1.8 kV. This is slightly less than Sztenc measured [5]. However, such dielectric strength can be considered sufficient for LV applications, in which energy absorbing varistor for current limitation is used.

3. Short fuse dielectric strength recovery

In CHCL the operating fuse is shunted by the semiconductor device connected in parallel, intercepting the current. The fuse-to-semiconductor current transfer, and next the semiconductor-to-energy absorber (MOV) one are controllable. It is important to avoid the latter operation before the fuse recovers its full dielectric strength. In Fig. 3 typical current and voltage profiles of CHCL operation are shown. The time T1 is the fuse arcing time, and T2 is the time of semiconductor state on. T2 has to be long enough to ensure the required fuse dielectric strength. On the other hand, its extension negatively affects the current limitation ability of CHCL. Therefore, T2 should be selected precisely.

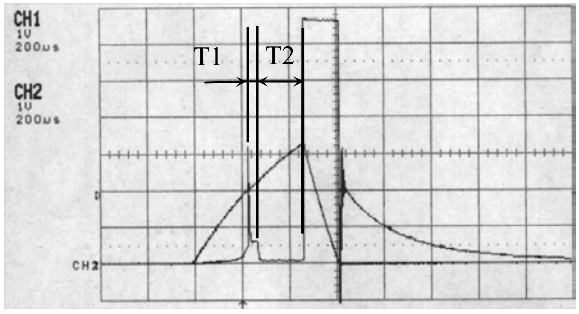

Fig. 3. Voltage and current profiles for CHCL operation: T1 – the arcing time, T2 – the semiconductor time on

The process of recovery proceeds under a very low voltage of a few volts associated with the semiconductor U_F. It can be faster than that in the case when the post-arc plasma is stressed by the rising recovery voltage delaying the discussed process.

A very important factor affecting the rate of strength recovery is the volume and the degree of ionisation of the post-arc gap, which depends on the current and arcing time. Therefore the experiments on the identification of the dielectric strength should consider the relationship between T1 and T2.

3.1 Conditions of experiments

Experiments were carried out in an oscillatory set-up and the typical CHCL assembly shown in Fig. 4. IGBT was used as the semiconductor device intercepting the current from the fuse. It was turned on and off by the controller 1, producing a pulse, lasting from 1μs to 100 ms. The controller operation could also be delayed in relation to the instant of the fuse arc ignition in the range of 1μs to 100 ms. The arc ignition was discriminated at the voltage level of +24 V.

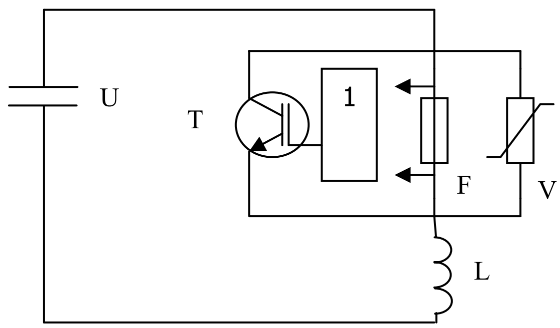

Fig. 4 Experimental set-up for identification of the short fuse dielectric strength recovery: F – the tested fuse, L – the reactor, T – IGBT, U – the

energy source (capacitor bank), V – energy absorber (MOV), 1 – IGBT controller

In order to facilitate exact measurements of the gap between contacts, the 0.1-mm ∅ copper fuse element was stretched between two askew cylindrical electrodes, Fig. 5. Such arrangement also reduced the effect of edges, which were moved away from the closest points, connected with the fuse element.

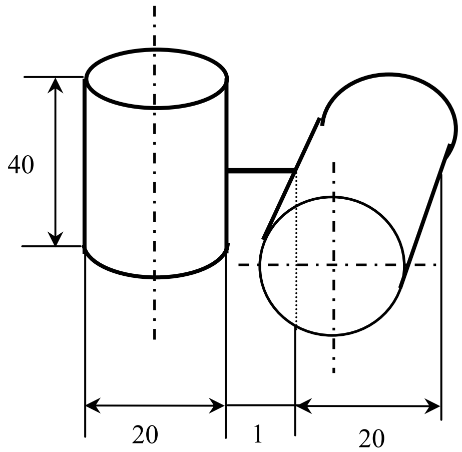

Fig. 5 Arrangement of electrodes for testing of dielectric strength recovery

3.2 Testing procedure

The test-circuit reactor was set in such a way that the capacitor bank of 2 mF charged up to 100 V produced the prospective test current of about 2 kA at the frequency of 480 Hz. High frequency ensured the rate of current rise higher than that at 50 Hz, almost by a factor of 10. Changing the time corresponding to the state on of the semiconductor device (T2) at a given constant arcing time (T1) the border conditions between successful and unsuccessful current interruption were identified. The record of successful interruption is shown in Fig. 3, and the failure is presented in Fig. 6. The arcing time T1 was changed in the range of 1 μs÷50 μs.

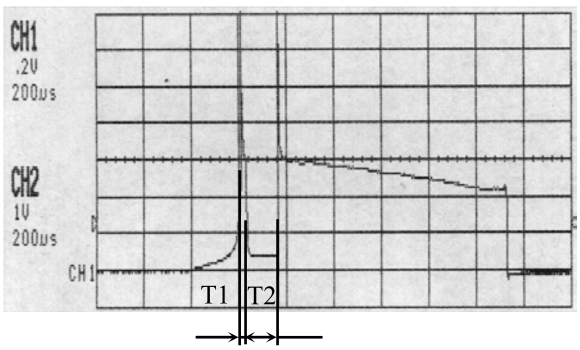

Fig. 6 Unsuccessful operation of current breaking with CHCL: T2 is too short

The voltage to be withstood by the short fuse was forced by the energy absorber, whose threshold voltage acquired 1 kV.

The relationship between the shortest permissible time on of IGBT and the arcing time is presented in Fig. 7.

4. Results of experiments

The experiments provide important information that an optimum arcing time T1 exists. For the relatively thin fuse element, used in experiments, it only amounts 15 μs. Both increase and reduction of T1 lead to the prolongation of recovery time of the fuse dielectric strength T2, corresponding to the recorded boundary time of IGBT on.

It was assumed that such a course of the recovery characteristic of the short fuse dielectric strength depended on two factors: the fuse element decomposition time and the temporal process of the arc ignition between electrodes.

No doubt, creation of a stable arc column needs time. Initially the arc plasma is cool and its volume is modest. With time the plasma extends and ionisation degree rises. The longer the process lasts, the more difficult and time-consuming deionisation. There is additional factor magnifying that process. The fault current rises as time. The longer the arcing time, the higher the arc current is. This has to affect the recovery time of the fuse dielectric strength.

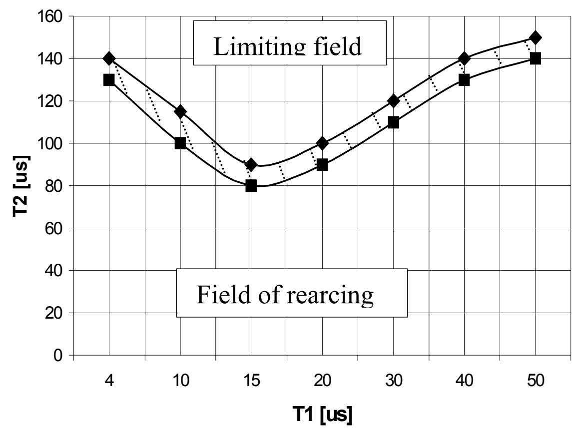

Fig. 7 The relationship between the shortest permissible IGBT time on and the arcing time of the short fuse

To estimate the possible influence of the fuse element decomposition on the recovery time of the fuse dielectric strength the energy dissipated in the fuse has been compared with the energy required for the fuse element decomposition. These energies have been calculated based on the recorded current and arc voltage traces, and the mass of the fuse element.

The deposited energy for the minimum T2 (T1=15μs) amounted to 0.22 J, while the fuse element decomposition requires 0.0067 J. In accordance to the actual knowledge, approximately 30% of the fuse element decomposition energy is sufficient to destroy the fuse element of a classical fuse. Supposed, this rule is also true for a short fuse, one can recon that the minimum time of the dielectric strength recovery is observed when the arcing time is strictly associated with the full decomposition of the fuse element.

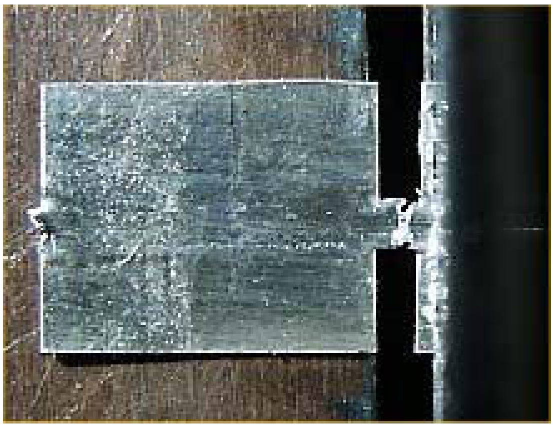

Fig. 8 The silver-strip fuse element after 1-μs arcing

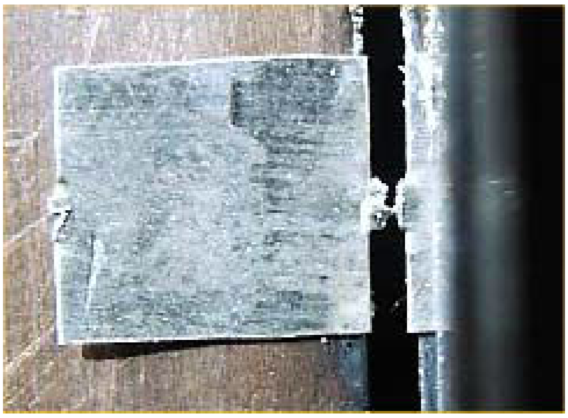

Fig. 9 The silver-strip fuse element after 2-μs arcing

Fig.10 The silver-strip fuse element after 4-μs arcing

In order to estimate the speed of the fuse element decomposition a few photographs of fuse elements were taken during the process of their disintegration. The fuse was shunted at a selected instant. In Fig. 8, 9 and 10 the silver-strip fuse elements are shown after 1 μs, 2 μs and 4 μs of arcing.

5. Conclusions

The fuse element of a short fuse for CHCL can be as short as 1 mm, since a 1-mm air-gap created after the fuse operation withstands more than 3 kV.

The relationship between the short fuse dielectric strength and the separation of electrodes is approximately a cube-root function.

The recovery of the short fuse dielectric strength depends on the rate of the fuse element decomposition and the time on of the semiconductor device shunting the fuse.

There is the optimum arcing time regarding the recovery of short-fuse dielectric strength. It is approximately equal to the time needed for the fuse element decomposition.

Acknowledgements

The research on contactless short-circuit current limiting devices has been carried out in frames of the current research project No: 8 T10A 058 21 supported by the Committee of Scientific Research in Poland.

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