A NEW METHOD OF CURRENT LIMITATION

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Abstract: A new idea of a hybrid contactless current limiter and its applications are discussed. On the substitution of a special ultra-short fuse for a contact switch in the hybrid current limiter a new device has been obtained, suitable for fast short-circuit fault clearing. The fuse role is only to operate at faulty conditions, forcing current transfer into a parallel semiconductor switch. Then the current is interrupted at an appropriate instant. In the practice no current breaking capacity of the fuse is required, since the voltage across terminals dictated by the semiconductor is less that that needed for arc ignition. Therefore an extremely short, axially cooled fuse element suffices, which enables the application of extremely high current densities in normal conditions. Consequently, fast, very high current limiters are easy to build. They can be helpful in the reduction of voltage dips.

Keywords: hybrid circuit breaker, current limitation, electric fuse, voltage dip

1. Introduction

Electric fuses are cheap, fast operating and reliable current breaking devices, and some of them can effectively limit short circuit currents. Regretfully, the latter feature depends on the generation of high arcing voltage, exceeding that of the power system. For HBC fuses such condition requires the application of a relatively long fuse elements. The longer the fuse element the worse the cooling conditions are, which means that long and massive fuse elements have to be used. Consequently, the arc extinction becomes difficult, and high-rated fuses, say for rated currents higher than 1000 A are not easy to build.

Therefore, a time ago the idea was developed, to apply two separate fuse elements [1]. One of them would start the fuse operation, and the other one – would be responsible for current interruption. This way two-paths fuses were invented, consisting of a very short, main-path fuse element with reduced cross-sectional area due to the effective axial cooling, and an auxiliary, long, low current HBC fuse connected in parallel with that main-path one. However, current transfer between parallel current paths requires the arcing voltage of approximately 100÷200 V in the main path to cover the inductive voltage drop along the commutation loop and that across the HBC fuse. This condition is difficult to fulfil, if a really short main fuse element is to be applied. Hence, auxiliary methods have to be used, such as the mechanical arc extension, complicating design of the two-path fuse, and slowing down its operation. At present, moderate ratings are merely available.

The trend of power quality improvement defines new requirements for the permissible voltage dips and current limitation conditions. In the case of high current installations there is a selection of current limitation devices available, but no one of them seems to be optimum. Neither fuses nor hybrid circuit breakers, combining the advantageous features of the contact and semiconductor switches can be considered flawless. Especially the latter depending on characteristics of the operating mechanism looks slow and bulky. However, a combination of a two-path fuse and a hybrid current limiter gives a new device, which can be called contactless hybrid current limiter (CHCL). It is relatively small, reliable, operates almost as fast as a fuse and is easy to build for quite high currents. One can expect that it should be significantly cheaper then other high current limiting devices.

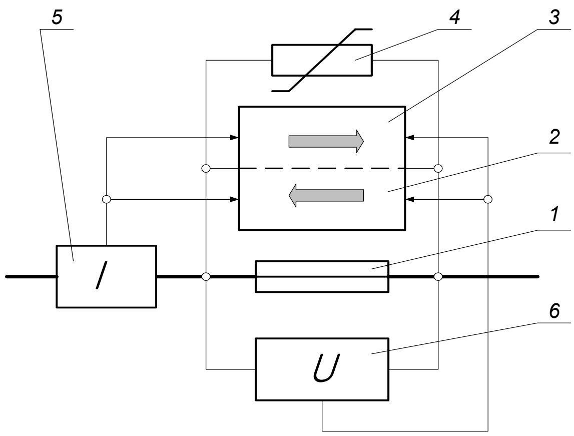

Fig.1 Contactless hybrid current limiter (CHCL): 1 – fuse, 2,3 – two-direction semiconductor switch, 4 – energy absorber, 5 – current sensor, 6 – voltage sensor

The idea of CHCL is presented on the example in Fig. 1. It is worth noting that here the branches of the two-directional semiconductor switch (2 and 3) are connected in parallel. However, in some cases, e.g. on the application of IGBT the connection in series is required.

2. Basic features of CHCL

If a fuse substitutes for the contact switch of a hybrid circuit breaker the conditions of operation of such CB change drastically. First of all, the current interruption process starts automatically on melting of the fuse element. This is a fast action and no intervention of any control system is required. No delay owing to the operating mechanism takes place. However, this also means that there is no way to control the circuit opening.

The CHCL minimum *t-I* characteristics entirely depend on the fuse.

On the other hand the current limitation and breaking conditions are closely connected with the semiconductor switching device. Hence, no current higher than that permissible for the transistor can be let through.

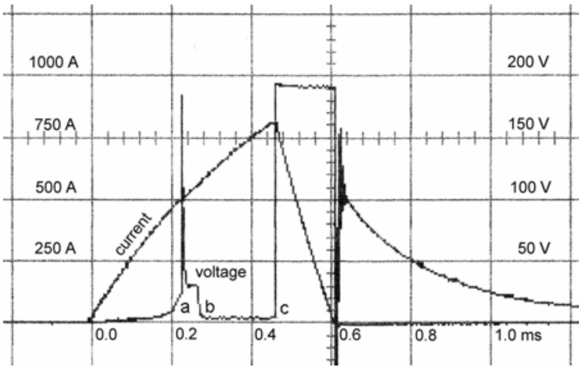

Fig. 2 CHCL operation: a – fuse arc ignition, b – transistor on, c – transistor off

However, it is worth noting that the current limitation level must rise as the recovery time of the fuse dielectric strength (time between points b÷c), Fig 2. This means that selection of a transistor, fixing the maximum permissible current through, is equivalent to a rough definition of features of the short fuse.

Say, the available transistor can turn 4 kA off, and the CHCL is expected to interrupt 100-kA prospective current rising at the rate of 40 A/µs. Then the short fuse must operate and recover dielectric strength in 100 µs.

3. Ultra-short fuse

Up-to-date semiconductor devices are fast and easy to control. There is no problem in their accurate turning on and off. Therefore it is the fuse applied in the CHCL that is responsible for basic features of the whole assembly.

3.1 Fuse element length

Since the fuse does not need to display any current breaking capacity, no arc quenching chamber or filler is required. The recovery of the fuse dielectric strength, after the fuse operation, proceeds fast under extremely low voltage (a few volts) enforced by the transistor turned on. After having turned the transistor off, the fuse dielectric strength is not affected by any parallel low-resistance elements, like polluted chamber walls. Therefore the gap between the fuse contacts can be significanntly reduced, which in turn permits application of very short fuse elements.

The short fuse element just connects massive electrodes, which must be separated in such a way that the gap created after the fuse element disintegration withstands the voltage enforced by the energy absorbing varistor connected in parallel. This means that a gap of 1÷2 mm in open air may be sufficient for LV applications, if almost uniform electric field is ensured. Experiments show that a 1-mm gap between electrodes with quite sharp edges withstands about 2 kV [2]. Filling the fuse with a compressed gas or applying vacuum, a similar gap can withstand much higher voltages. Thus, for both LV and HV applications extremely short fuse element can be used, which ensures its very effective axial cooling.

3.2 Fuse element cross section

Even very thin fuse elements, can carry relatively high load currents, when they are short enough. For instance it was tested that a 1 mm long, silver fuse element with the cross-sectional area as small as 0,07 mm^2, needed at least 180 A to melt [3], which is equivalent to $j \sim 2.5$ kA/mm^2. In this case the ratio $l/\sqrt{S}$ of the fuse element length l and the side $\sqrt{S}$ of the square calculated from the fuse element cross-sectional area S amounted to 3.8. When $l/\sqrt{S}$ reduces, the axial cooling improves, and a higher fuse element current density is allowed. Consequently, a short fuse element with $S \sim 1$ mm^2 may be sufficient to carry several-kA working currents.

3.3 *t-I* characteristics

In contrast to classical fuses very strong axial heat conduction affects the course of fuse *t-I* characteristics, even at very high prospective currents [4] slowing down the fuse operation in the whole range of interest, Fig. 3.

To show the difference between classical and ultra short fuses two lines **a** and **b** corresponding to the Meyer's (1) and the Preece's (2) rules for a long copper fuse element with $S = 0.108$ mm^2 are drawn. These lines constitute asymptotes of *t-I* characteristic for a simple, long fuse element in free air cooled by convection at low overcurrents or heated adiabatically, without energy exchange at high short circuit currents.

$$\int_0^t i^2 dt = K_M S^2 \qquad \text{(Meyer)} \qquad (1)$$

$$I_{melt} = k_m d^n \qquad \text{(Preece)} \qquad (2)$$

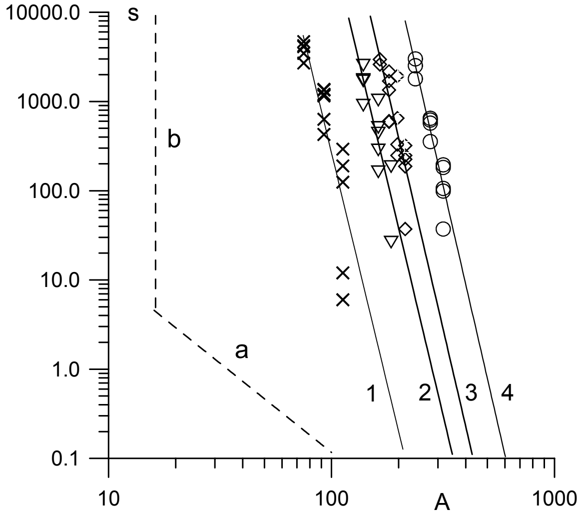

Fig. 3 Short fuse *t-I* characteristics for a variety of fuse element thickness and materials:
1 - Al 200 μm, 2 - Cu 108 μm, 3 - Ag 91 μm, 4 - Ag 124 μm, a – Meyer, b – Preece [4]

Looking at the experimental *t-I* profiles presented in Fig. 3 one can notice that all of them incline in the same manner, which means that the relationship between the temperature increase $\Delta\vartheta$ and the current density j for various fuse element materials and cross sections only differ by a coefficient.

When cooling by heat axial conduction preveils, in quasi static conditions, the power deposited in the fuse element $P_{el} = P_{cond}$, which means that for constant heat sink temperature and a fuse element unit length:

$$\frac{\rho_0\,(1+\alpha_\rho\,\Delta\vartheta)}{S}\left(j\,S\right)^2 = 2\,\lambda_0\,(1+\alpha_\lambda\,\Delta\vartheta)\,S\,\Delta\vartheta \quad (3)$$

and consequently

$$\Delta\vartheta = \frac{\rho_0\;(1+\alpha_\rho\,\Delta\vartheta)}{2\lambda_0\,(1+\alpha_\lambda\,\Delta\vartheta)}\;j^2 \quad (4)$$

The temperature increase $\Delta\vartheta$ is independent of the fuse element cross-sectional area, or its shape at a given current density.

Both the electrical and heat conductivities influence $\Delta\vartheta$ in the same manner: inversly proportional. This relationship is true for quasi static conditions, i.e. for a few kA/mm^2, or moderate overcurrents. At very high fault currents the effect of the axial heat conduction reduces, and that of the heat absorption by the fuse element rises pushing the *t-I* characteristic closer and closer to the Meyer's line. Neither in such a case the cross-sectional area of the fuse element affects *t-I* profiles for a given current density j^2.

To avoid extremely thin fuse elements for low-rated fuses, special alloys may be more practical than commonly used silver and copper.

The time needed for the fuse element decomposition is always very short, even at relatively low overcurrents. The distribution of temperature shown in Fig. 4 demonstrates that only a very short segment of the fuse element can melt and break. Next the burn-back of remaining fuse element stumps, as short as 0.5÷1-mm takes little time. Recorded times of the fuse element decomposition only acquired a few microseconds.

3.4 Fuse characteristics shaping

It is worth noticing that the fuse element connection with terminals (electrodes) significantly affects the temperature distribution. The broken line visible in Fig. 4 marks the temperature of the fuse element at the points of connection. It is quite high. By selection of an adequate solder, the metallurgic effect can be achieved, facilitating the *t-I* curve shaping. The length of the connection and physical features of solder may also affect these characteristics at short circuit currents.

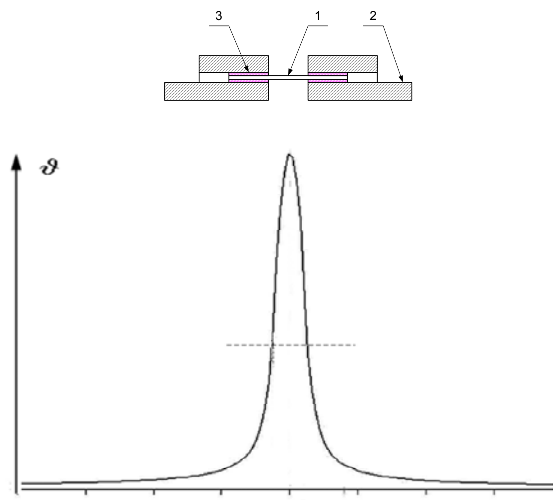

Fig. 4. Temperature distribution along the short fuse:
1 – the fuse element, 2 – terminal, 3 – solder, 2-mm horizontal division

3.5 Arcing voltage

The domination of axial cooling affects the arcing voltage, which behaves similarly to that of the arc burning between plates of a chute. It is very stable and amounts to approximately 25 V for the fuse element length of 1 mm, Fig. 5. This is in agreement with the rule stating that the cooling effect proportional to the arc cross-sectional area produces a constant arcing voltage. Its value is sufficient for the enforcement of fuse-to-semiconductor device current transfer. It is worth mentioning, that much higher arc ignition voltage, Fig. 2, can facilitate fast current transfer in contrast to classical contact switches used in hybrid current limiters.

As the discussed ultra short fuse is not equipped with any arc quenching means, the recovery of dielectric strength is only ensured by the recombination and diffusion. Both of them proceed quite slowly.

Luckily, the recovery time depends on the transferred current, and not on the fault prospective current, or limited current, as the plasma remained to deionise is associated with the former. Comparing ultra short fuse and a simple contact switch, one can come to the conclusion that no essential difference in their recovery processes can be expected, as the mass of the fuse element is extremely small and in some cases may be even compared to a contact bridge. The only important feature is the presence of remnants of the fuse element, when the arcing time is too short, which may substantially reduce the voltage withstood. This means that the parallel semiconductor switch must be controlled precisely to ensure optimum conditions of current limitation.

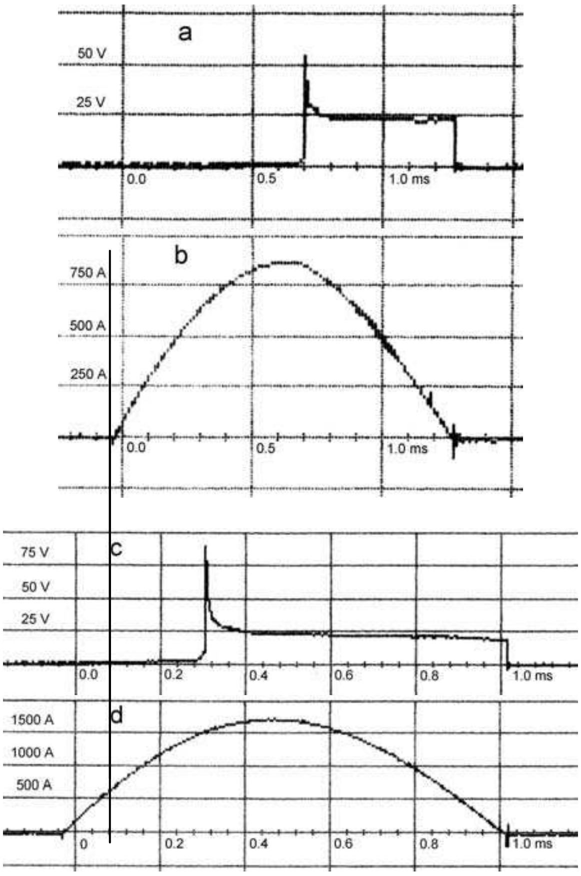

Fig. 5 Current and arcing voltage traces of an ultra short fuse for two different prospective currents: the silver fuse element, 1 mm long with the cross-sectional area of 0,07 mm^2

The power losses ΔP at working currents depend on the fuse element volume V for the assumed current density j.

$$\Delta P = \rho \, (1 + \alpha_\rho \Delta \vartheta) V \cdot j^2 \tag{5}$$

For a copper fuse element, 1 mm long, 0.5 mm in diameter, at j = 2.5 kA/mm^2 the power losses acquire 50 W. It is not much, if one considers that such a fuse is designed for approximately 1-kA rated current.

General features of the ultra short fuse have a lot in common with the comparable ones of the contact bridge.

3. Design of CHCL

Application of a very short fuse element facilitates design of a compact fuse, with external dimensions smaller than those of a semiconductor diode for comparable rated current, owing to less power losses. One can estimate, the fuse only dissipates about 10% of the diode power losses.

Hence the fuse can be made in a pill form with relatively massive contacts. It is worth mentioning that the bulk of heat generated in the fuse can be dissipated by adjacent terminals or even radiators, which help reducing contacts dimensions. Thus, the depositable fuse may be extremely small and cheap. It is demonstrated on the example in Fig. 6.

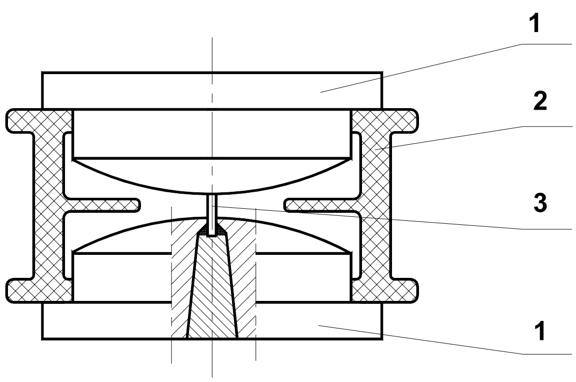

Fig. 6 Example design of an ultra-short fuse

Other parts of the CHCL are multi-use and durable. Transistors only pass the current through over, say, 100 μs. So they do not need radiators. The control unit must only be fed during the operation. Hence, a battery will do. Example design of CHCL is shown in Fig. 7.

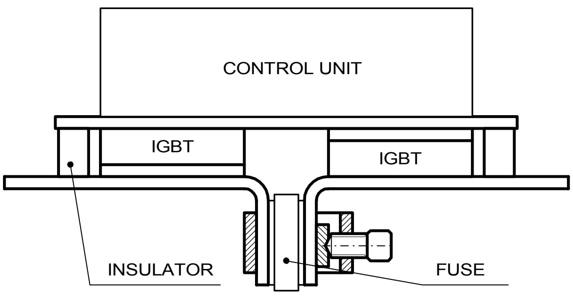

Fig. 7 Example design of CHCL

4. Application

CHCL is a compact, 1-phase, very fast-operating LV current limiter, easy to build for high working currents, above the limit of classical fuse applications. The high voltage design is possible, however economically it is less attractive. CHCL looks like one-shot device, however the only depositable part is a small fuse, cheap and easy to replace. The current limiter features depend in a great extend on that fuse.

Such characteristic indicates the possible fields of CHCL applications. It is perfect for back up or life protection in high current circuits, especially in marine and industrial power systems. It may protect high current rectifiers and convertors.

Owing to its fast *t-I* characteristics CHCL is well suited rather to short circuit current limitation and interruption than overcurrent protection.

5. Conclusions

On substitution of an ultra short fuse for the contact switch in the hybrid current limiter a new current limiting device, CHCL, is developed with special characteristics.

The short fuse is fully responsible for *t-I* characteristic, while the current interruption capacity depends on the semiconductor device in parallel to the fuse.

The short fuse offers fast *t-I* characteristics due to effective axial cooling by means of heat conduction.

CHCL is well suited for current limitation. Its characteristics of overcurrent interruption are difficult to form; however some possibilities exist.

The fuse element can be as short as 1 mm for both LV and HV applications if only adequate gas filling and pressure will be adopted.

The limited current is higher then the fuse element melting current due to the required time for the recovery of the fuse dielectric strength. The latter depends on the fuse arcing time.

The relationship between the recovery time of the fuse dielectric strength and the fuse arcing time shows a minimum associated with the fuse element decomposition and arc plasma temperature and volume.

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