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► **To cite this version:**

Rémy Ouaida, Jean Francois de Palma, Gilles Gonthier. Hybrid Protection based on Pyroswitch and Fuse Technologies for DC Applications. Symposium de Genie Electrique, Jun 2016, Grenoble, France. hal-01361696

HAL Id: hal-01361696

<https://hal.science/hal-01361696v1>

Submitted on 7 Sep 2016

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Hybrid Protection based on Pyroswitch and Fuse Technologies for DC Applications

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Abstract – Fuses and Circuit Breakers play an important safety role in electrical transportation systems. Challenging new applications, especially in DC, have brought conventional current limiting devices to their limits. Indeed, mechanical circuit breakers may be too slow to open for networks with large DC fault currents. On the other hand, fuses may be too slow to open with very low DC fault currents. For AC applications, the natural zero crossing will help clear fault currents. In DC applications, the no natural zero crossing makes clearing faults by conventional current limiting technologies difficult. This paper presents a new solution to protect DC transportation using a fuse and pyroswitch hybrid system. This will apply to PV generation, energy storage, Electric Vehicles.

Index Terms— Hybrid Over Current Protection, DC Application

I. INTRODUCTION

Historically, fuses and mechanical circuit breakers - general purpose and fast acting - have been the choice for Over Current Protection (OCP) devices. Furthermore, each time electrical applications have reached new steps and brought up new challenges in fault clearing, these have been answered by solutions including fuses and/or breakers. Is this still the case today?

Figure 1 reflects the current/voltage rating requirement matrix of different existing and future DC applications. The current and voltage for these applications range between 500V-1500V and 200A-1500A. MERSEN has been developing new products/technologies which respond to various DC system requirements [1-5]. Nonetheless, conventional OCPs have been pushed to their physics limits, in terms of performance, size, and costs.

Fuses have been protecting electrical systems for as long as the existence of electricity. Specifically, for more than a century, current-limiting fuses provide low cost, easy-to-install, compact, fast and reliable over-current protection for electrical systems from distribution networks, to switching power supplies. Being the most fail-safe and compact solution, since 1950, current-limiting fuse technology has evolved its speed, power rating, and adapting to more extreme working conditions, to protect semiconductor devices or equipment in the new power electronics era. However, limited by thermal physics, fuses' non-controllable nature makes them difficult to address the very basic requirements from transportation DC

applications, which are generally demanding for product size, temperature rise, power cycling capability, and precise protection over comparatively low fault current to distribution networks (typically, kAs in battery systems versus tens of kAs in distribution networks).

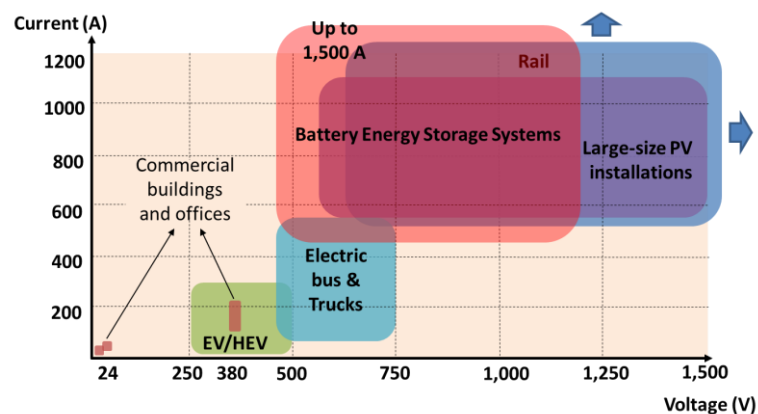


Figure 1: Estimated current and voltage of existing and future requirements in DC application

On the other hand, circuit breakers are also widely used for short-circuit protection. Their ability to be reset is a major advantage against fuses. Moreover, circuit breakers feature a lower on-state voltage drop in the closed position as well as a galvanic separation in the open state. However, when a fault is detected, breakers operate more slowly than current-limiting fuses due to the large mechanical time constant. In DC networks, the presence of arcs leads to contact erosion and arcing chamber fatigue, i.e. a shorter lifetime and high maintenance costs. A longer time to react to a large fault current leads to higher let-thru current, which will ultimately stress the downstream circuit they are intended to protect

Of course, fuses and circuit breakers can and should always be improved to adapt to new application requirements, but they will nevertheless always be based on the same fundamental principles. This paper presents a novel solution based on a hybridization of fuses and pyroswitch components that may answer new DC protection needs. In this paper, the operation principles of this hybrid OCP will be described, and test results will be shown as validation of design. Finally, a

comparison between the characteristics of the new protection and a conventional fuse will be shown.

II. NEW OVER CURRENT PROTECTION

A. Pyroswitch

Mersen, previously Ferraz Shawmut, developed pyrotechnic devices in the 80's rated 1 kV to 24 kV AC/DC – 2kA to 10kA. These Pyristors [6] were selected and are still sold in AC/DC applications including, but not limited to, wind tunnels, cycloconverters, and high distribution. Low power pyrotechnic safety devices took off in the early 1990's in the automotive industry with the introduction of the first airbags in European vehicles' steering wheels. The pyroswitch is an electrical interrupter and, in contrast to a fuse, the time to achieve a complete disconnection of a circuit will not be dependent on the magnitude of the over current. In general, a pyroswitch utilizes a miniature guillotine that is propelled by a pyrotechnic charge to achieve the force required to cut through a metal conductor (busbar) as described in figure 2. This gives a very simple and thus extremely reliable behavior [7-9]. The pyroswitch has no impact on the electric system before operating since it is positioned above the busbar. After operation, it cuts the busbar and separates/isolates the two conductors. The cut-off time is lower than one millisecond. Figure 2 presents a sectional view of a pyroswitch developed by Herakles Safran [10]. The copper bar is depicted in orange, the initiator is illustrated in yellow and the blue part represents the guillotine.

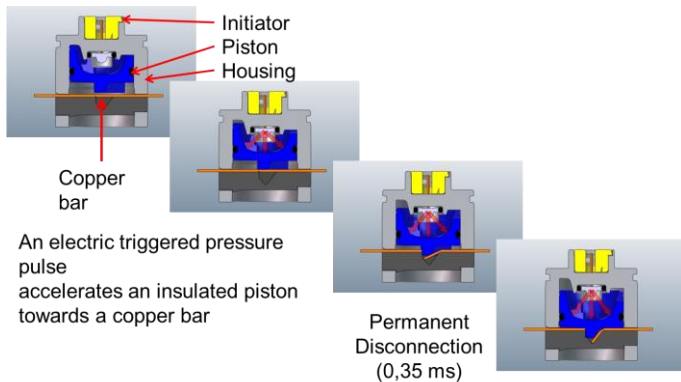


Figure 2: Sectional view of a pyroswitch

A pyroswitch alone is compatible with medium power devices (electric device) at $I \sim 400$ A and $V \sim 50$ V. Any increase in the current range requires increasing the section of the busbar, thus increasing the energy in ignition required for disconnection. Similarly, any increase in voltage will require more distance between the conductors after the busbar is cut, and thus complicate the device and make it bigger.

Even if a pyroswitch has the advantage that it is faster operating than a strictly mechanical apparatus and is much less expensive than are purely electrical breakers in high load applications, this kind of device suffers from several drawbacks. Notable among these is the risk of harmful arcing when cutting off an inductive circuit. A simplified explanation for this is that the circuit with inductive current is reluctant to change. This reluctance causes a harmful arc between two

formerly connected conductors at the moment of disconnection. In contrast to the type of “soft” arc that appears anytime when a circuit with no inductance (i.e. a capacitive circuit) is disconnected, an arc under influence of inductance will not be easily extinguished. While the reasons for these deficiencies are not straightforward, the failure in the pyro breakers under high loading may be due to their inability to rapidly turn off the ionization between electrode parts.

Preliminary tests have been done on a pyroswitch alone to understand the limitation of the ability to protect a DC system. The first test was a 200V, 250A with a very low L/R of 200 μ s. Figure 3 shows pictures of a pyroswitch after a loading test. The device has cut off the circuit but a dark stain has appeared on the copper bar, due to the reluctance. The breakdown voltage after the test was also abnormally low (dielectric test =500V). Another test with a lower voltage of 150V has been performed and the breakdown voltage after the ignition was as expected (i.e. >5kV). Thus 150V seems to be the limitation of this pyroswitch.

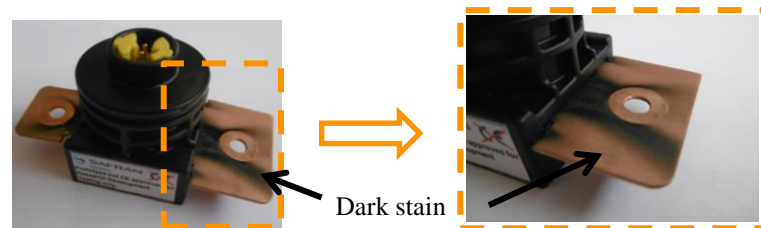


Figure 3: Pyroswitch pictures after a loading test (200V-250A-L/R=200 μ s)

It is therefore one object of this paper to provide a high speed, high voltage hybrid OCP device capable of minimizing system exposure to circuit faults.

B. Hybrid solution: Pyrofuse

This section presents a new hybrid protection solution, in which a pyroswitch element and a fuse element are configured electrically in parallel. Figure 4 shows the pyroswitch (grey) and the fuse (white). The parallel configuration means the designer can choose the best components of each type. Indeed, the fuse and the pyroswitch interact with each other. This section presents the steps in their behavior.

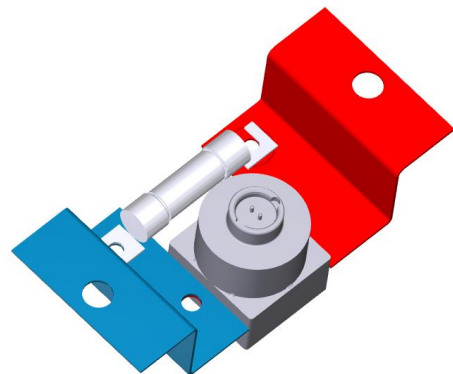


Figure 4: New hybrid protection solution with pyroswitch and fuse in parallel

Figure 5 presents the electrical schematics of the pyrofuse. The fuse F1, the pyroswitch P1 and the electronic triggering system are depicted. During its lifetime, the entire device is closed and the nominal current is flowing. The P1 resistance (copper bar) is lower than the F1 resistance. For instance, with a 400A pyroswitch, the on-state resistance is around $200\mu\Omega$ and the resistance of a fuse is around 1-2 m Ω . Thus most of the nominal current (80% - 90%) flows through P1. Cycling performance and lifetime are improved in comparison to a simple fuse. Moreover, with the very low resistance of the entire system ($\sim 200\mu\Omega$), the on-state losses drastically decrease. Fuse F1 could be sized with a low nominal current caliber (10 – 20 % of I_N) and thus a low cost.

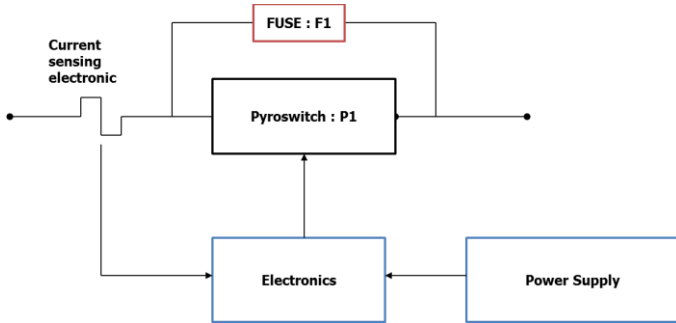


Figure 5: Electrical Schematics of the Pyrofuse

Let's focus on the cut off. When the current abnormally increases because of a failure in the DC application, a sensor (Hall Effect or shunt) detects the fault current and sends the triggered signal to P1 thanks to a control board. As seen before, pyroswitch systems suffer from a risk of harmful arcing when cutting off a high voltage load. But in this case, a fuse F1 is situated in parallel and is still closed. Thus P1 cuts the copper bar without any voltage and the fault current flows through F1. As this fuse is underrated, it opens the circuit with a very short cut-off time (less than 300 μ s). To summarize, the fuse is sized for the nominal voltage and underrated for the current. This new protection makes it possible to cut off high voltage (until 1500V) and high current (400-800A).

III. PERFORMANCES

This section presents the performances of the new OCP. The on-state characteristics will be described (losses, temperature) and the cut off behavior will be presented.

A. Normal current carrying

In order to understand the on-state performances, the system has been tested with a nominal current of 400A. The losses have been measured between 20W and 30W at 25°C with a nominal current of 400A. These values have been simulated with a parallel system composed of a fuse with a resistance of 1 m Ω and a pyroswitch of 200 $\mu\Omega$. These estimations of resistance are similar to the previous section, and confirmed by our measurements.

The system has been put in an oven to control the ambient temperature and connected by terminal connectors with a section of 240 mm² (corresponding to the standard). As the resistance is very low, the temperature rise is limited. Figure 6

shows the simulation of the temperature rise for an I_N of 400A in the pyroswitch blade, which is the hottest spot in the system.

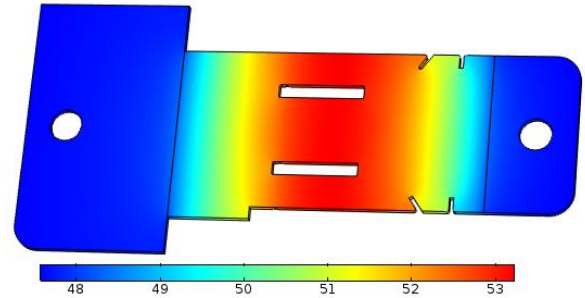


Figure 6: Simulation of the blade in the pyroswitch with $I_N=400A$ at 25°C

Table 1 summarizes the temperature rise results obtained by simulations and tests. The system temperatures are similar for 25°C and somewhat different for 60°C and 90°C. The reason could be the actual air flow in the oven versus the condition of convection coefficient in our simulations. However, the system has interesting performances with low losses in on state.

| Ambient temperature | System temperature (simulations) | System temperature (tests) |
|---------------------|----------------------------------|----------------------------|
| 25°C | 53°C | 55°C |
| 60°C | 87°C | 70°C |
| 90°C | 116°C | 99°C |

Table 1: System temperature under 400A (tests and simulations) versus ambient temperature

B. Fault protection

Mersen has a test center doing LV and HV electrical tests: short circuit making and breaking, transient current withstand and operation in high current rate of rise conditions. All these tests can be done in AC or DC. The high power test lab has 3 different test cells to cover all the required levels of voltage, current and power:

- 3 MVA test cell: Voltage can be adjusted up to 800V with a short circuit up to 8000A r.m.s.
- 20 MVA test cell: Voltage can be adjusted between 50 and 1000V with a short circuit up to 35 000A r.m.s.
- 400 MVA test cell: A turbo-generator driven by a 1300 kVA synchronous converter delivers the current. Voltage can be adjusted from 100V to 45kV with a maximum r.m.s. short circuit current of 305kA.

For our tests, the 20 MVA test cell has been used under 500 VDC to 1000VDC with a fault current of 1000 A to 7000A. A special test board has been developed to initiate the pyroswitch. This board has been composed by capacitors which discharge 8A in the initiator when the opening order is given. With this current level, the pyroswitch opens the copper bar in 300 μ s. Figure 7 presents the waveforms of the current and the voltage during the cut-off for a 7000A fault current under 1000VDC. The total clearing time is 1.5 ms. We can see an overvoltage

during the cut-off due to the arc in the parallel fuse. This overshoot could be reduced by replacing with another fuse with a different fuse element [11]. In this test, the parallel fuse had a range of 63A thus the minimum fault current the system could open was 400A in 50 ms. The total clearing time could be split in three steps as described in (1):

$$\begin{aligned} \text{Total clearing time} = \\ \text{Pyro ignition} + \text{Fuse pre-arcing} + \text{Fuse arcing} \end{aligned} \quad (1)$$

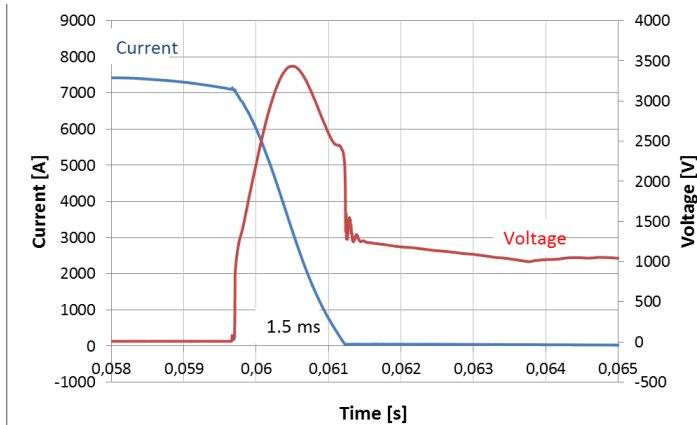


Figure 7: Current and voltage waveform for a fault current of 7000A – 1000VDC

As seen, the estimation of the total clearing time could be established with the pyro ignition time (independent of the fault current but dependent on the ignition current) and the fuse pre-arcing and arcing time (dependent on the fault current). Figure 8 presents the total clearing time versus the rms current and the overload that the system could support. The clearing time for the pyrofuse is very selective because it is nearly independent of the fault current. Indeed, between 400A and 600A the device protects the application in less than 50 ms and for a fault current higher than 600A within 3 ms. Moreover the pyrofuse endures overload without deterioration (curve AA'). For instance, an overload of 7000 A could flow through the device during 100 ms. These characteristics make the pyrofuse a customizable product with a tunable time-to-current curve, which is not the case with a conventional fuse.

The next section presents the pro and cons of the pyrofuse compared to fuses.

C. Comparison between pyro and conventional fuse

Whereas AC applications keep on growing at a moderate rate, MERSEN has encountered a booming demand in DC protection [12], dealing with fast emerging markets such as EV/HEV, battery storage, data-center, PV, traction or electric aircraft. To answer this, Mersen has developed a complete range of DC OCP devices. Among them, we can find fuses and pyrofuses and this section presents the comparison between the two technologies.

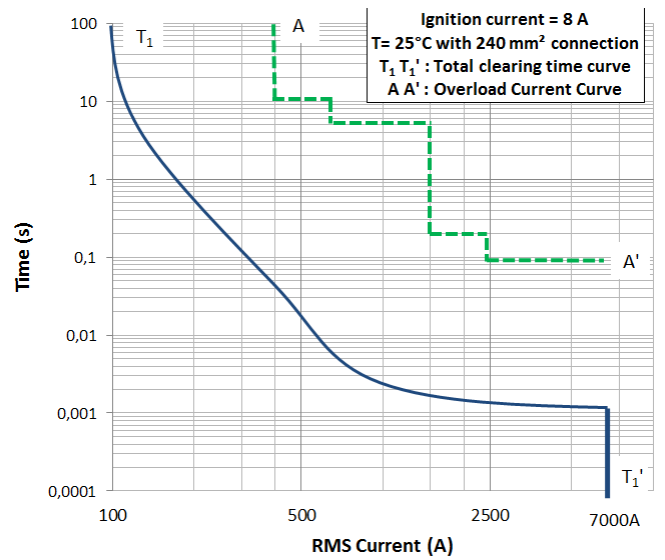


Figure 8: Total clearing time and overload current

First let's focus on the advantages for each solution. Today DC fuses are ultra-fast acting fuses for large fault currents with a cost effective and a proven technology. A pyrofuse is a fast acting protection with a low cost technology. The conduction losses are close to zero and the system operates for small or large fault currents (fully configurable). Table 2 summarizes the performances of the different technologies. Both products are not resettable because they are used as an ultimate protection. The time to clear the fault is independent of the current for the pyrofuse and the time-current curve is totally tunable which is not the case for the fuse. The new solution has an excellent cycling performance with low conduction losses.

| Family | DC fuse | Pyroswitch + fuse |
|----------------------------------|-----------------------|-------------------|
| Resettable | No | No |
| Time to clear high fault current | Excellent, 10 μ S | Good, 1 ms |
| Time to clear low fault current | Slow to melt | Excellent |
| Cycling performance | Limited | Excellent |
| Conduction losses | 80W (400A) | 20W (400A) |
| Tunable Time-Current curve | Limited | Yes |
| Self-powered | Yes | Possible |
| Average market price | Low | Low |

Table 2: Summary of the comparison between the pyrofuse and fuse

The new OCP has many benefits but the main problem is the electronic command. Indeed, this solution is not self-powered as a fuse and current sensor and electronic have to be added. In some applications, it is impossible to put this electronic in the required volume. For these reasons, a self-triggered pyrofuse has been developed. The next section will present the principle and the characterization of the ultimate protection.

IV. ULTIMATE PROTECTION

A. Principle

As seen before, pyrofuse protection shows excellent performances (cut-off time, volume, weight and cost). Unfortunately, in some applications, the current control command is not straightforward. Moreover, some protections need to be self-triggered to ensure ultimate protection of the electrical installation. All these reasons have led us to develop the self-triggered pyrofuse.

Figure 9 depicts the patented self-triggered pyrofuse (a) in nominal conditions and (b) with a fault current. Let's focus on the nominal conditions. The schematic shows the same pyrofuse in green, with pyroswitch PS1 and the parallel fuse F1. PS1 is split in two paths: the ignition one depicted by a resistor and the power one where the nominal current flows inside. In the previous section, the user had to add a control electronic to trigger the system. In this solution, the principle is to add a fuse (F2) in series which is designed for the nominal current but not for the nominal voltage. This fuse is used as current sensor and power generator for the pyroswitch trigger. In nominal conditions, current flows through F2 and PS1. If a fault current appears (figure 6 (b)), an electrical arc arises between the terminals of fuse F2. At this moment, nothing can stop the arc because F2 is not designed for the nominal voltage. This arc will be used as a voltage source by the initiator. R1 defines the current flowing in the ignition of PS1 and controls the opening speed of PS1. After the ignition, the principle is similar to a conventional pyrofuse described in the previous section. When the pyrofuse opens the circuit, the arc in F2 disappears and the entire system protects the application without external electronic.

The advantage of this system is that it is self-powered, similar to a conventional fuse. As F2 is not designed for the nominal voltage, the fuse has a small size and low watt losses. Thus the total losses are still lower than a conventional fuse.

The drawback is the lack of selectivity in the time current curve that we could have with the electronic control command. However, with a low voltage fuse, the selectivity is more easily tunable. The next section presents the test results.

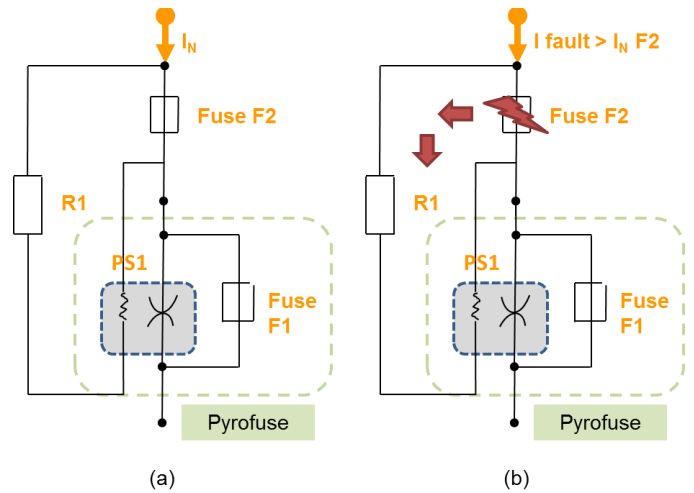


Figure 9: Schematic of the self-triggered pyrofuse in (a) nominal conditions and with (b) a fault current

B. Test results

In order to validate the self-triggered pyrofuse principle, several tests have been done in our labs. It has been tested under 500VDC with 11 kA fault current and the results will be presented in figure 10. The current is depicted in blue and the voltage in red. It is possible to share the wave form in 4 steps. Step 1 is the beginning of the short-circuit with the increase of the current through fuse F2 and PS1. When the current reaches a certain value, an arc appears in F2 (step 2) which increases the voltage and limits the current. During this step the energy of the arc is conveyed to the pyroswitch. In step 3, PS1 is triggered and the current flows in F1. This fuse melts, causing an overvoltage and a drop in current. At this moment the arc in F2 has not enough energy to be maintained. In step 4 the system has protected this application with a voltage of 500V and no current.

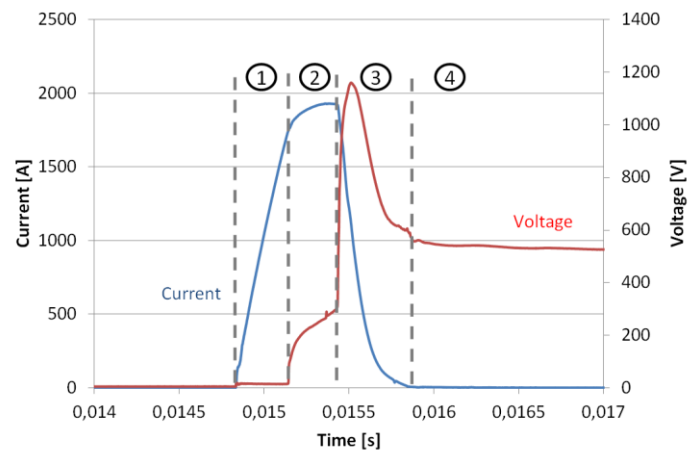


Figure 10: Waveforms of the current and the voltage during the switch-off

The advantage of the system is the limitation of the fault current which never reaches the maximum value. Moreover, this solution is completely autonomous.



Figure 11: Self-triggered pyrofuse - XpST

Figure 11 presents the self-triggered pyrofuse we have developed at MERSEN. The entire system has a height of only 70 mm, a length of 135 mm and a width of 65 mm.

For automotive application, the pyrofuse and the self-triggered pyrofuse have many advantages:

- Respond to DC transportation requirements
- Excellent time to clear the high and fault current
- Excellent cycling performance: load profiles in EV applications are becoming more complex. The cycling performance for the pyrofuse is independent of the load profile which simply the design.
- Very low conduction losses.
- Low average market price

V. CONCLUSION

This paper presents a new overcurrent protection device for DC applications. The conduction path made by the pyroswitch and the clearing path made by a fuse bring the best of the 2 products, i.e. low voltage drop, high inrush current capability, high cycling performance, fast cutting of the busbar. Moreover the fuse presents an excellent capacity to clear high DC current. Tailored to the final application, these 2 devices bring the best performances for Low Voltage DC applications up to 1500VDC like EES, EV, PV, and DC distribution.

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