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PYROTECHNIC SWITCH WITH FUSE FUNCTION

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Abstract. The article will present the combination of a low-voltage fuse with a pyrotechnic switch in compact design. The limited switching capacity of the very simple pyrotechnic switch is increased considerably when combined with a fuse which has classical passive time/current characteristic and high switching capacity. FEM calculations will demonstrate the functional principle and the passive and active characteristics of functional models will be examined. Switching behaviour with different overcurrents in case of passive or active triggering will be discussed on the basis of measuring results. The behaviour of such a fuse with high impulse currents will also be presented.

Keywords: fuse, pyrotechnic switch, impulse current, numerical simulation, SPD.

1. Introduction

For more than 100 years, overcurrent protective devices in the form of fuses and switches have been successfully enhanced and adapted for the most diverse networks, consumers and protective objectives. The massive modification of the power supply networks which is currently underway also places new demands on these protective devices. As numerous power generators feed electricity into the grid, the flow of power in the distribution network is no longer just unidirectional, but frequently bidirectional. What is more, the source characteristics of numerous electricity generators and the new regulating mechanisms for controlling the power flow reduce the short-circuit currents in the grid. Both effects influence, among other things, the tripping conditions for overcurrent protective devices in the power grid. In order to keep up with requirements, additional compact and low-cost functions are needed alongside the optimum configuration and selection of devices.

Fuses have the advantage over switches that they are smaller while ensuring an extremely high short-circuit breaking capacity and that they have a very high current limitation and thus low total clearing integrals. In addition, they are inexpensive and do not exhaust ionised gases. The disadvantage, however, is that fuses only protect devices and systems once and that they respond slowly in case of small overcurrents which results in long melting times and also long arcing times over some half waves. In case of such small currents, the installation conditions and the ambient temperatures frequently have an impact on the disconnection behaviour. With the modification of networks described above, these disadvantages may come to the fore.

Switches, in contrast, have the advantage that the overcurrent performance is easily adjustable and that they can often be externally triggered. This external triggering by additional monitoring devices allows safe disconnection in a relatively short period of time, even in the event of faults which do not directly cause high short-circuit currents or in networks where the operating and short-circuit current are almost equal. In networks with active power regulation, however, the passive protection characteristic of protective devices is frequently only decisive if these triggering systems fail. As with high short-circuit currents, the one-time switching function in combination with external triggering is therefore sufficient in case of such faults.

For this reason, a combination of separate circuit breakers and backup fuses has become an established part of medium-voltage systems to get the benefit of the advantages of both devices [1]. Measures aimed at disconnecting small currents faster have been available for fuses for many years. To this end, e.g., exothermal masses are used which passively or actively heat the solders on fuse-elements or directly heat subareas [2]. These procedures can considerably reduce the natural melting time, however, disconnection within 10 ms, as is common with switches, cannot be achieved. It is also common knowledge that disconnection of fuses can be accelerated by a short-circuit enabling fast disconnection times, at least directly after the short-circuit has been generated [3]. This, however, requires conventional networks with a high short-circuit power. An overview of the different approaches can be found in [4].

The principle of the I_S - Limiter, namely parallel connection of a pyrotechnic switch and a fuse, is known from the field of high-voltage [5]. This principle can also be used for low-voltage applications at a small design size. Similar devices have also been developed for the automotive sector and DC systems. However, these devices require a trigger signal and have neither a passive short-circuit performance nor, without additional programming, a defined time-current characteristic. The design targets for the switching device for low-voltage applications were:

- ☐ High passive short-circuit breaking capacity of a low-voltage fuse
- ☐ Time/current characteristic of a low-voltage fuse without triggering
- ☐ Size and costs similar to those of a fuse
- ☐ Additional feature: External triggering with a disconnection time < 30 ms
- ☐ High capacity to carry impulse current, particularly lightning currents
- ☐ Nominal current up to approx. 250 A
- ☐ Nominal voltage up to approx. 400 V AC

2. Set-up and components of the approach examined

The sample solution consists of components of an enclosed fuse, size 22x58. This size is borderline in every way with regard to the desired values, however, this approach allows a realistic assessment of the physical limits and the construction volume required for implementation.

Conventional compacted silica sand was chosen as a quenching medium. Two parallel copper fuse-elements with modulation, which were, as far as possible, installed straight through the housing, were used for the required high impulse current carrying capability. The nominal current of the two fuse-elements is 250 A. The fuse can carry lightning impulse currents with an amplitude of 25 kA (wave form 10/350 µs with $I^2t = 156\,\mathrm{kA^2s}$). Thus a configuration was selected by which the nominal current and impulse current are at the upper limit, resulting in maximum requirements on the switching capacity. Consequently, lower values can be used for the same size or the same values can be used for larger sizes.

A very simple pyrotechnic switch was integrated between two separated sand-filled parts of a fuse. The restricted sections of the fuse-element required for disconnecting the short-circuit current are distributed evenly between the two parts of the fuse-link. Figure 1 shows the basic test set-up with an electric match.

A hollow space a2 is located between the two separated sand-filled parts a1 of the fuse-link. The two parts a1 of the fuse-link filled with silica sand are separated from the hollow space a2 by a thin wall < 1 mm so that no arc extinguishing medium can enter the hollow space. A cutting blade c is situated in the hollow space between the two separated parts of the fuse-link nearby the fuse-elements b.

Consequently, only little force is required to actuate the cutting blade. The overall width of the hollow space is smaller than 5 mm. The two copper fuse-elements b routed directly through the two sand-filled parts of the fuse-link and also through the hollow space a2. The two fuse-elements b are connected with

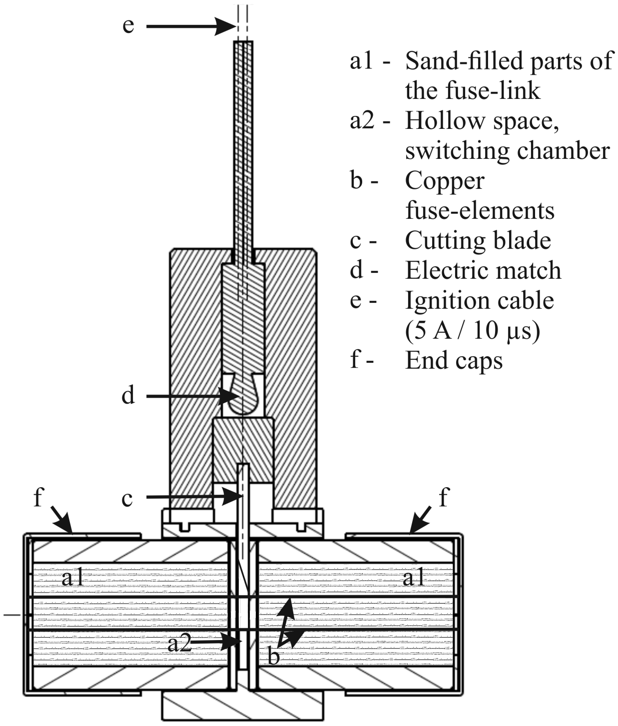

Figure 1. Test set-up with actuator.

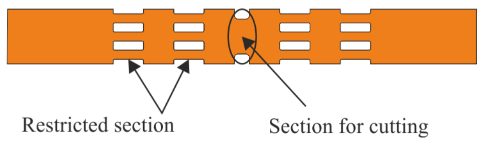

Figure 2. Fuse-element with restricted sections and additional section for cutting.

the end caps f. The fuse-elements have an additional restricted section in this hollow space which is dimensioned in such a way that it does not trip in case of the common tripping integral of the fuse when short-circuit currents are interrupted. Figure 2 shows a single fuse-element.

This additional restricted section does not melt over the entire time/current range as long as the fuse shows normal passive behaviour. It simply reduces the force required for the interruption of the fuse-elements b. The arrangement of the hollow space, the thin walls, the cutting blade, the additional restricted section and the electric match constituted a simple pyrotechnic switch. This pyrotechnical switch has a limited self-switching capacity. The electric match can be ignited with a short current flow (5 A, 10 µs). The cutting blade disconnects the fuse-elements. An arc can burn back the fuse-element up to the two parts of the fuse-link filled with silica sand where then the arc safely quenched at the latest to the next current zero.

3. Functional principle

3.1. Passive function

The time/current performance (heating until melting of one restricted section of the first fuse-element) of the sample arrangement was simulated based on FEM calculations of transient impulse currents up to the current which melts the fuse after 1 h and compared with a conventional fuse [6]. Figure 3 shows the temperature rise of the fuse-element when impulse current flows through it. The calculated time/current characteristics were compared with real currents in the range of about 600 A to 50 kA. The characteristics are illustrated in Figure 4 and show enough concordance.

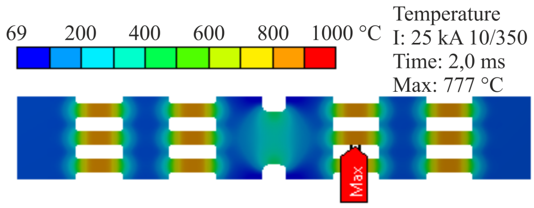

Figure 3. Calculated maximum temperature at 25 kA, 10/350 µs impulse.

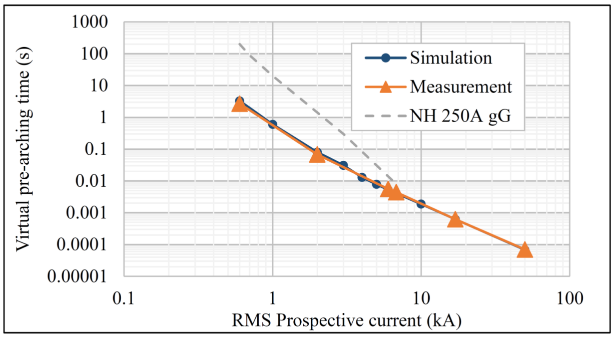

Figure 4. Comparison of the measured with the calculated passive time/current characteristic.

The passive switching performance (no triggering over the ignition cable) of the sample arrangement was tested at 440 V in the current range of 600 A to 50 kA. Figure 5 shows the current and voltage characteristic at 50 kA compared with the characteristic of a conventional fuse design.

3.2. Active function

In addition to the passive function, the function of the pyrotechnic switch was also tested under load (overcurrents). The ignition of the electric match and the current load of the test arrangment were managed via a time-dependent sequential control. In this context, the trigger time T_{Delay} and the time until both fuse-elements are disconnected T_{move} are relevant. The resulting delay T_V defines the maximum current load which has to be mastered. Figure 6a shows the disconnection of a current of 600 A and Figure 6b the disconnection of a current of approx. 2 kA.

In principle, extremely high short-circuit currents are only switched passively. According to the passive time/current characteristic, currents > 3 kA are only interrupted passively. The pyrotechnic switch was modified for accelerated triggering for the test

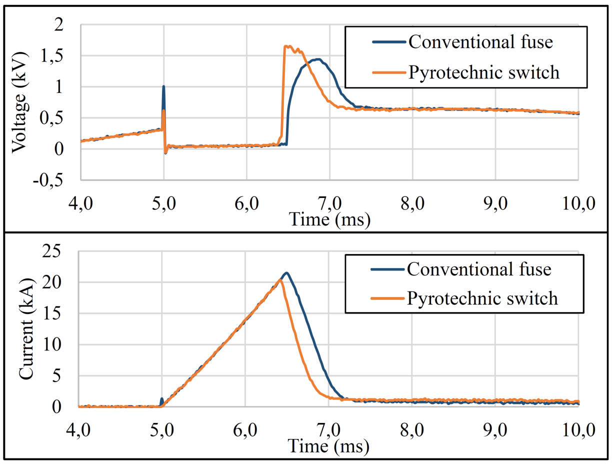

Figure 5. Measured voltage/current characteristic at I_p = 50 kA AC of the conventional fuse and the pyrotechnic switch.

in Figure 6b. The test current in Figure 6b and the switching capacity of the pyrotechnic switch thus already exceed the maximum capacity of the switch. This high switching capacity of the simple pyrotechnic switch and the combination with the passive protection characteristic of the fuse thus allow safe and reliable series connection both in case of active and passive functions.

Figure 7 shows the passive time/current characteristic and the actual active characteristic. It becomes evident that the sample arrangement examined ensures safe disconnection at 440 V over the entire current range within a duration of < 30 ms. In case of a longer delay or non-triggering, the arrangement shows the time/current performance of a fuse with the relevant characteristic.

4. Condition after impulse current load

In addition to the time/current performance and the switching capacity, the condition of the fuse-element was assessed after a sequence of impulse current loads which correspond to a normative load of type 1 surge protective devices [7]. Figure 8 shows such a fuse-element. The restricted sections have changed colour, but this is uncritical. No partial melting resulting from excessive current densities or deformations of the fuse-element caused by electrodynamic forces were found.

After the switching loads, which were mastered with active and passive function, the impulse withstand voltage (insulation) was also tested by determining the impulse sparkover voltage of the sample set-up. It became evident that in case of active disconnection the impulse sparkover voltages were always > 6 kV independent of the load current. This is identical with the value achieved with short-circuit currents in case of passive function. Without active function, only electric strengths which are partly below 2 kV occurred when passively switching currents by means of fuse-

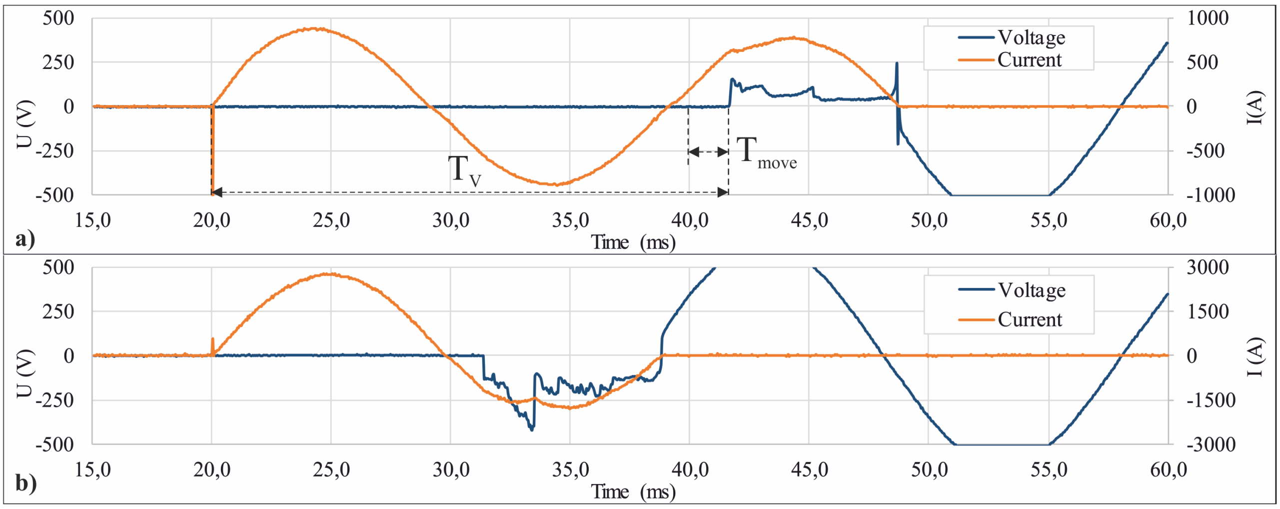

Figure 6. Measured voltage/current characteristic in case of disconnection for: a) I_p = 600 A (U_C = 434 V, cos(φ) = 0.92); b) I_p = 2 kA (U_C = 434 V, cos(φ) = 0.83).

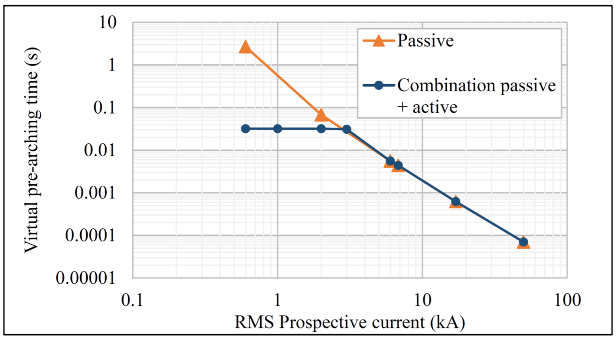

Figure 7. Measured time/current characteristic of the pyrotechnic switch.

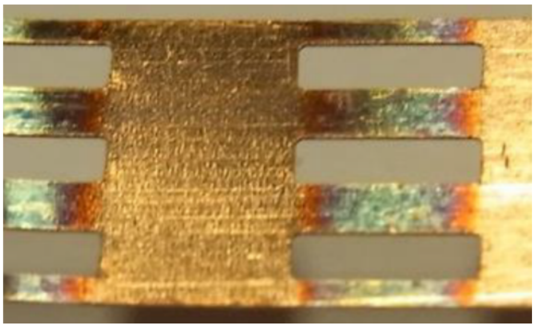

Figure 8. Colour change of the restricted sections after normative load.

elements in the seconds range (interruption of only one restricted section per fuse-element). The sample arrangement examined thus safely prevents repeated current flow through the fuse after disconnection even in case of higher voltages.

5. Summary

The sample arrangement presented in this paper is a space-saving and cost-effective compromise for networks, plants or equipment for which a one-time switching function is sufficient. It was demonstrated that high switching capacities and low total clearing integrals similar to fuses of comparable size can be achieved by means of additional triggering. The disconnection time in case of external triggering is the same as in case of conventional externally triggered switching devices. If triggering fails, the protective effect is equivalent to that of a normal passive fuse so that at least conventional overcurrent and short-circuit protection is ensured. Moreover, the sample arrangement can safely carry high transient impulse currents. Safe active disconnection is ensured independent of the current load, namely from zero current to the short-circuit current range, thus achieving a higher and at the same time defined electric strength compared to passive fuses.

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