ACI – an innovative design concept for SPDs

White Paper

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Surges can be induced in low voltage systems by switching operations, for example switching inductive load, when fuses are triggered or by faults like short circuits or earth faults. Another cause of transient overvoltages in low voltage systems is atmospheric events like, e.g., lightning strikes to a lightning protection system or supply lines, but also strikes in the vicinity whose induction effect can lead to overvoltages.
Surge protective devices (SPDs) are installed in many different places to protect sensitive devices and installations from the effects of surges. The components used in modern SPDs stand out for their high capacity and simultaneously good protective properties. The technology applied varies according to the required capacity and the specific requirements at the point of installation.
Thus, high performance spark gaps are often used with, e.g., type 1 SPDs suitable for discharging partial lightning currents. Whilst the spark-gap technologies applied have a suitably high capacity and are robust, they can, however, generate mains follow current and must, as a rule, be energetically coordinated with further protective steps. Type 1 SPDs are usually installed at the point where the low-voltage supply enters a building.
Type 2 SPDs are suitable for discharging and limiting overvoltages caused by switching operations or inductive coupling. Here, the energy content of the impulse currents to be discharged is significantly lower than that of the partial lightning currents which must be dealt with by type 1 SPDs. The active protective components in type 2 SPDs are often high-performance metal oxide varistors (MOVs) which are characterised by a relatively high discharge capacity and do not allow any mains follow current.
These technologies have been around for years and are employed by many different manufacturers. The relevant product standards IEC 61643-11 [CITATION IEC03 \l 1031] and EN 61643-11 [CITATION EN610 \l 1031] lay down the minimum requirements for SPDs which not only ensure that the devices fulfil the specified parameters in the relevant application, but also that they behave in a defined and safe way in case of failure due to overload or at the end of their service life.
However, the changing requirements in the installation environment, like the increased application of high-performance electronic components, fluctuating short-circuit capacity and instable network conditions mean that, in future, different and higher demands will be put on SPDs which could lead to overloading or failure. For this reason, there are additional requirements with regard to the behaviour of SPS in case of failure [CITATION Platzhalter1 \l 1031].

Failure scenarios for SPDs

Generally, one can differentiate between failure of SPDs as a result of overloading or simply because they have come to the end of their service life. Whilst failure at the end of the service lifetime is usually an ongoing process, e.g., brought about by numerous discharge processes, overloads often involve individual and short-lived events. Overload can, for example, be caused by the occurrence of high impulse currents which exceed the designated discharge capacity.
Fundamentally, the failure scenarios for SPDs depend on the technology applied. Spark-gap-based SPDs do not age, for example, as a result of the given network voltage and are not as sensitive to superimposed, high frequency interference such as can be invoked by switching power semiconductors [CITATION GCh05 \l 1031] (**Figure 1**).
MOV-based SPDs are also directly connected to the mains voltage, but they are much more sensitive to fluctuations or superimposed interference. The curve of an MOV can be influenced by, e.g., high energy impulses (amplitude or duration), by a number of impulses with a lower energy content (**Figure 2**) or by permanently increased leakage currents. A slow fall of the

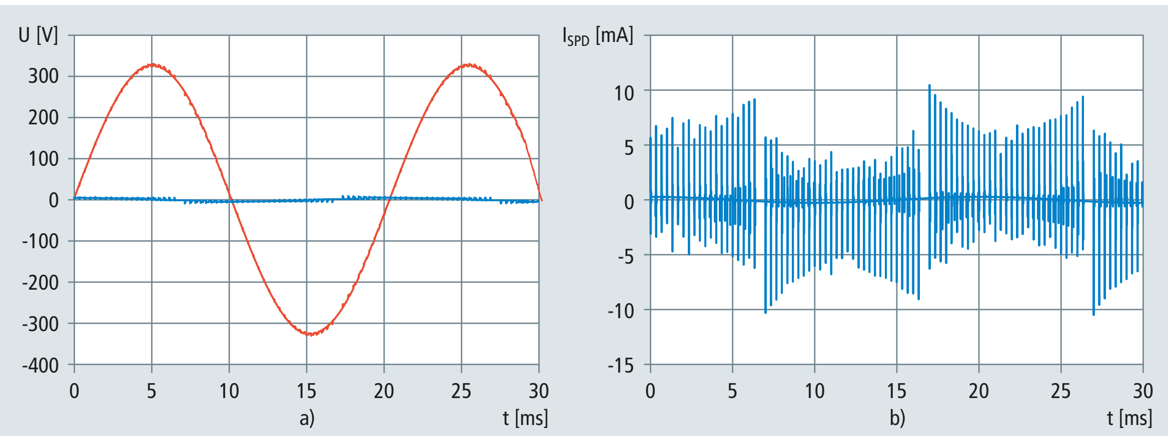


Figure 1 a) Voltage and current on an MOV-based SPD with U_c = 275 V, installed at the output of a PWM-controlled inverter and b) current through the MOV

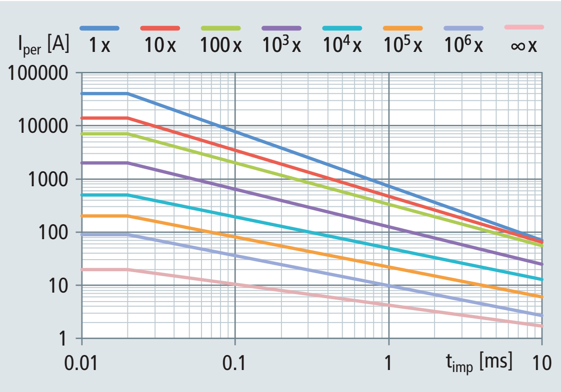


Figure 2 Permissible impulse current I_{per} for an MOV depending on the duration of the impulse and the number of impulses (based on the derating curves of the manufacturer)

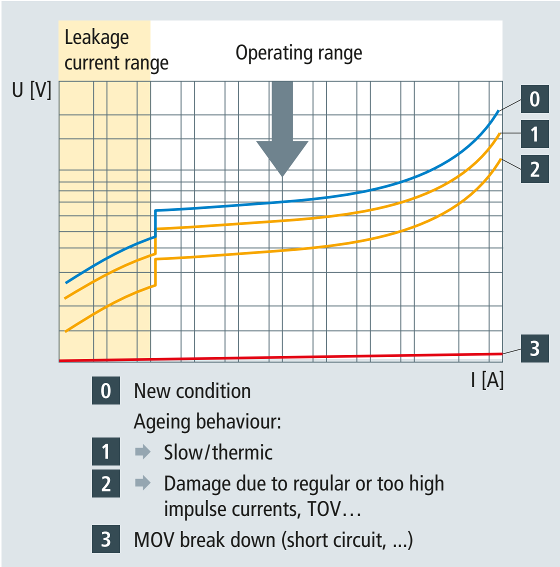


Figure 3 MOV – changes to curves (schematic representation)

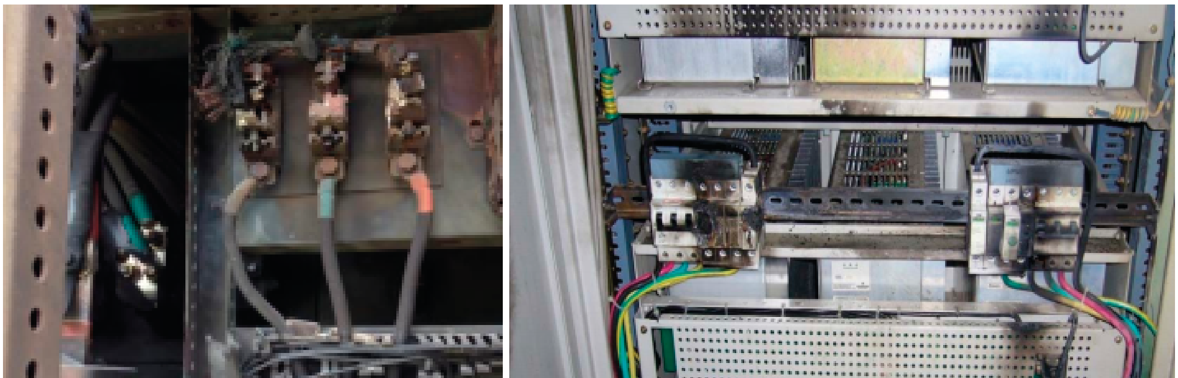
U/I curve of an MOV generally leads to a continuous increase in the leakage current and thus to a rise in the temperature of the MOV. Before the temperature can reach an intolerable level, the SPD is safely and reliably disconnected by the integrated thermal disconnector.

The sudden, complete breakdown of an MOV as a result of an impulse with high energy content, however, leads to the irreversible destruction of the grain boundaries in the MOV ceramics and thus to a low impedance fault pattern. The resulting short circuit current must be dealt with and disconnected by an integrated or external overcurrent protective device (OCPD). **Figure 3** presents a schematic summary of the changes to curves.

The applicable product standards [CITATION IEC03 \l 1031], [CITATION EN610 \l 1031] already contain tests which check the failure behaviour. MOV-based SPDs are usually not only protected by integrated thermal disconnectors, but also by internal or external OCPDs like, for example, fuses or circuit breakers.

To ensure that the upstream installed OCPD (fuse or MCB) will not be tripped or even overloaded by the impulse current itself, the OCPD should have a high current rating. If the impulse current exceeds a given limit the OCPD will be destroyed (**Figure 4**).

However, if one examines the disconnection characteristics of a fuse or circuit breaker, it becomes apparent that the disconnection time is relative to the occurring fault current. For example, seconds pass before fault currents in the region of a few hundred amperes are disconnected, whereas large short circuit currents are interrupted in a matter of milliseconds.



Fuses overloaded by impulse currents

Power supply with MCBs overloaded by impulse currents

Figure 4 Fuses and MCBs overloaded by impulse currents

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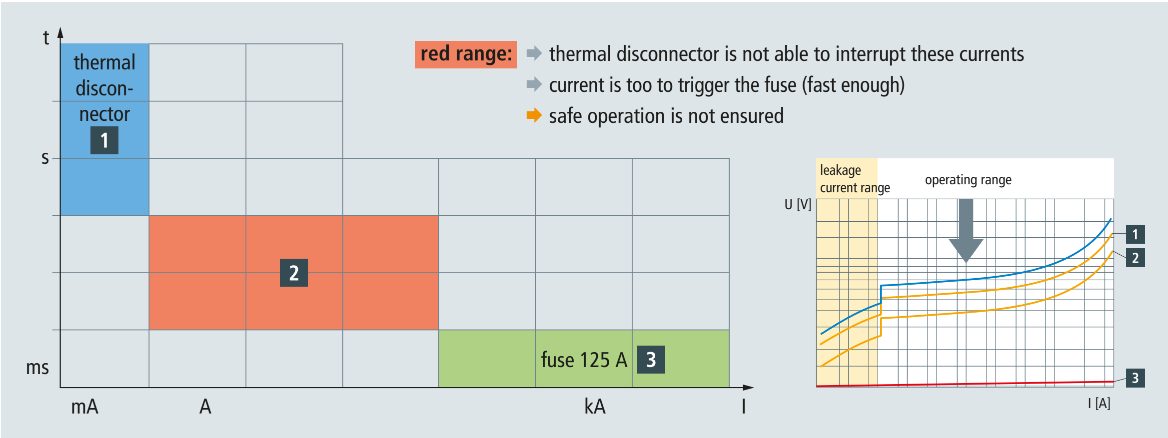


Figure 5 Standard application using a fuse

Disadvantages of hitherto existing solutions

In modern SPDs with MOVs as protective elements disconnectors which are thermally coupled with the varistor ceramics are a simple and effective way of interrupting any leakage currents of up to several amperes.

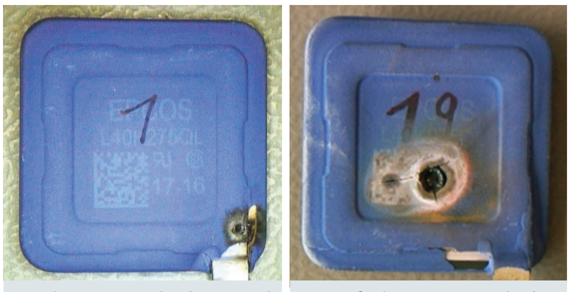
However, if the leakage current increases too quickly, the thermal disconnector may not be activated quickly enough. This is, for example, the case when the curve change in the MOV results from a long term existing temporary overvoltage. Such temporary, power frequency overvoltages are caused by faults in the low-voltage network, like the loss of the neutral conductor or short circuits between the phase conductor and the neutral conductor. If the resulting leakage current exceeds a certain amount there will be a very rapid change in the curve of the varistor – the varistor breaks down and becomes conductive. In this case, the fault current rises rapidly and the thermal disconnector fails to disconnect the SPD from the low-voltage power supply. Furthermore, the relevant OCPD (fuse, circuit breaker) is also incapable of providing reliable protection for the MOV and thus the SPD because the OCPD might not be triggered due to limited fault current. **Figure 5** schematically shows the ranges of slow (1) and faster changes of MOV v/i-characteristics (2) up to short circuit (3) as well as the relevant protection ranges.

A further fault scenario which could lead to the inadmissible overload of an MOV-based SPD is the undefined failure behaviour of the MOV itself. If an MOV breaks down due to a very large impulse current, a significant residual resistance, depending on the impulse energy introduced and the homogeneity of the MOV ceramics, may remain which limits the arising short-circuit current (**Figure 6**). In this case, too, the upstream fuse or circuit breaker cannot protect the SPD because there is either no or very belated tripping.

The problem is heightened by the fact that back-up fuses often have high nominal current values to prevent them from being tripped by impulse currents discharged by the SPD (**Table 1**). This frequently leads to a "gap in protection" which depends

Nominal values for NH fuses		Impulses (8/20 µs), which cause the fuse to trip [kA
I_n [A]	I^2t_{min} [A^2s]	
35	3030	14.7
63	9000	25.4
100	21200	38.9
125	36000	50.7
160	64000	67.6
200	104000	86.2
250	185000	115

Table 1 Impulse capacity of NH fuses



Impulse current 5 kA (10/350µs) | TOV fault current 50 A (4 s)

Figure 6 Failure behaviour of an overloaded MOV

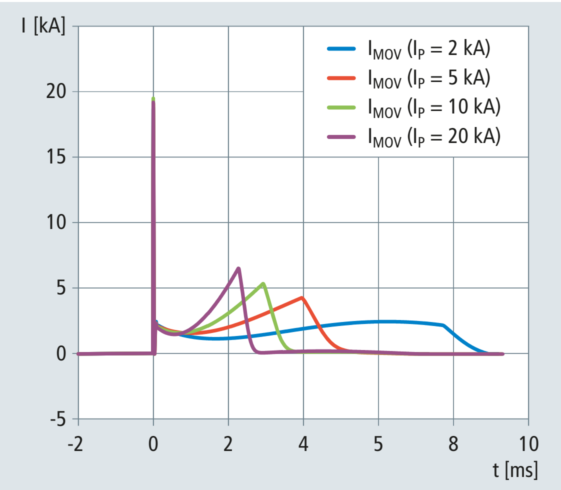


Figure 7 Time sequence of the fault currents when the SPD is overloaded by an impulse current (Parameter: prospective short circuit current at the point of installation)

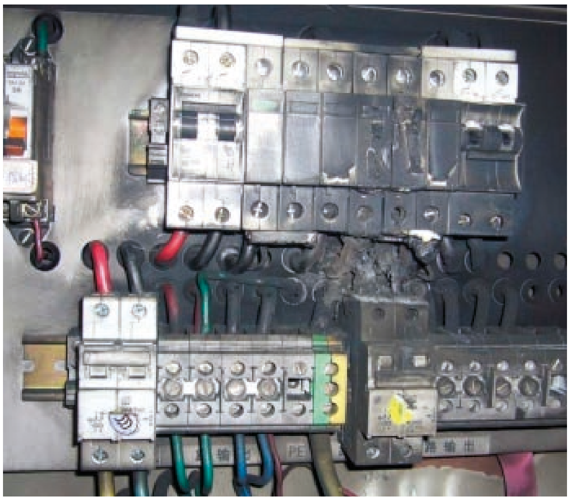


Figure 8 Overloaded SPD and distribution board destroyed by short-circuit current

Prospective short circuit current I_p [kA]	Maximum value of the fault current I_{fault} [kA]	Total disconnection time t_{off} [ms]	Energy dissipation in the SPD (impulse + fault current) W_{total} [J]
2	2.5	8.8	800
5	4.0	5.5	610
10	5.2	3.8	515
20	6.4	2.8	440

Table 2 Load parameters for the overloaded SPD according to Figure 7

on the nominal current value of the fuse and the actual short-circuit current.
Internal fuses which are better adjusted to the possible failure behaviour of the SPD are often used in modern SPDs, however, a certain gap in protection may remain.
Figure 7 shows the results of a simulation (U_n = 230 V, fuse 100 A Gg) emulating the failure of an MOV-based SPD following an impulse load of 20 kA (8/20 µs). For the simulation, it was assumed that the varistor broke down following the impulse and subsequently had a constant residual voltage of 50 V. This value corresponds with the average value recorded in numerous overload experiments. It becomes clear that the emerging fault current depends on the prospective short circuit current I_p, the phase angle Ψ and the residual voltage u_{MOV}. The greatest loads were recorded for a switching angle of $\Psi = 0°$.
In **Table 2** the energy loads are shown, that were detected for the SPD in case of the fault currents shown in **Figure 7**.
It can be seen that relatively long disconnection times t_{off} are registered for small prospective short circuit currents I_p whereby a very high amount of energy W_{total} is generated in the SPD although the maximum value of the existing fault current I_{fault} is low. In case of failure, this energy in the SPD turns into pressure and heat and can overload the SPD before it is safely disconnected from the low-voltage power supply (**Figure 8**).

New approach

The disadvantages described when protecting overloaded SPDs can be overcome if a high performance switching element is integrated in the SPD. This switching element must, on the one hand, be capable of rapidly interrupting or even preventing currents in the milliampere or ampere range and, on the other, quickly and reliably interrupt fault currents in the range of the prospective short-circuit currents.
Whilst mechanically activated switching devices like, for example, circuit breakers, always have a time lapse when detecting fault current, triggering and moving the switching contacts, the switching element described here is activated by the surge itself. At the same time, it should not, or only minimally, affect the protective behaviour of the SPD, i.e., neither negatively affect the discharge capacity nor the protection level for the whole SPD. **Figure 9** shows the basic construction of such an MOV-based SPD with integrated, high-performance switching device and deactivation circuit.

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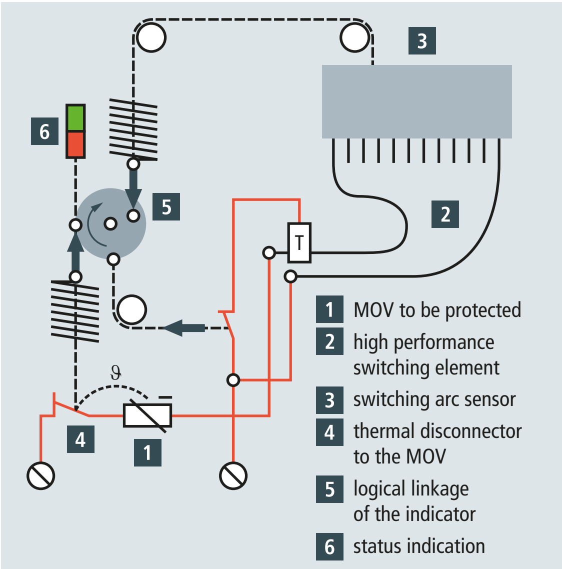
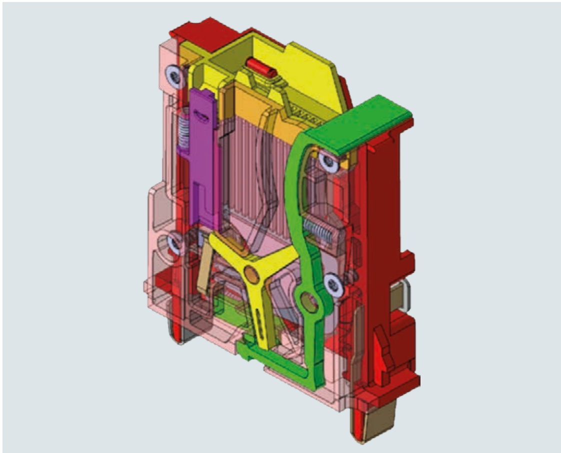


Figure 9 Basic construction of an SPD with integrated high performance switching element



Technical Data	
nominal voltage AC (U_N)	230/400 V
max. operating voltage (U_C)	275 V
nominal discharge current (I_n)	20 kA 8/20 µs
max. discharge current (I_{max})	30 kA 8/20 µs
short circuit current rating AC (I_{SCCR})	25 kA
additional ext. overcurrent protection	Not needed
protection level [L-PE] / [N-PE] (U_P)	< 1.5 kV
TOV withstand min.	440 V
temperature range	-40 ... +80 °C

Figure 10 Overload resistant type 2 SPDs with ACI technology

The established switch / spark-gap technology provides such a high performance switching element (**Figure 10**).
In a module width of only 18 mm the functional elements MOV with thermal activated disconnector, high performance switching element as OCPD and related monitoring and status indication are integrated (**Figure 11**).
The special design of these triggered switch / spark gaps makes it possible to achieve low sparkover values and at the same time high discharge capacities. **Figure 12** shows the protective behaviour measured when loaded with the nominal impulse discharge current I_n = 20 kA (8/20 µs).
In addition, the integrated ACI (Advanced Circuit Interruption) switching unit prevents leakage currents because it provides reliable insulation under normal conditions. This reliable insulation also enables a high temporary overvoltage (TOV) withstand, far higher than the values required in the product standard.
As the ACI switching unit is activated by every overvoltage event, there is no time lapse like that entailed with other surge protection devices when detecting and triggering a switching device. The ACI switching unit thus has a small disconnection integral which is selective to a 35 A gG fuse. This allows a connection cross-sectional area ≤ 6 mm² and eliminates unwanted interaction with upstream OCPDs.

Safe failure behaviour when MOV overloads

An MOV can also be partially or completely destroyed and fault current generated when using an MOV-based SPD with ACI switching unit.

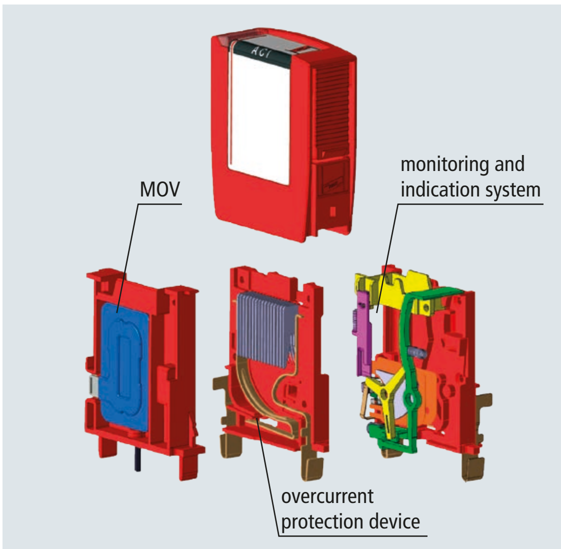


Figure 11 Design of the SPDs with ACI technology

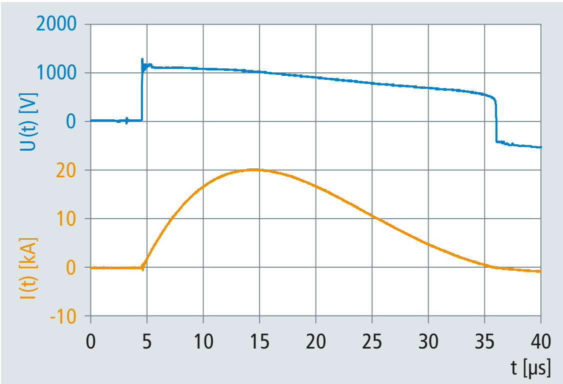


Figure 12 Residual voltage measured on an SPD with ACI technology

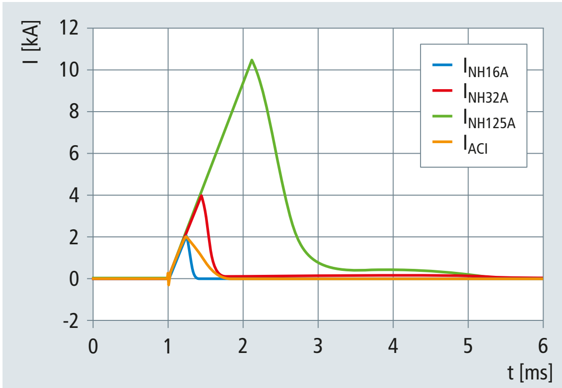


Figure 13 Short-circuit disconnection on an SPD with ACI technology in comparison to gG type fuses with different rated currents (measurements)

The ACI switching unit, which is activated simultaneously with the surge event, is capable of quickly interrupting this fault current, hence protect the SPD against excessive load. In order to demonstrate the effectiveness of the ACI switching unit, the integrated MOV was shortened (to emulate MOV failure) and tested on a high-capacity source at U = 255 V, I_p = 25 kA and ψ = 45 °. Additionally, the let-through current of the ACI SPD is compared with the let-through current of different gG type fuses (**Figure 13**).
The high-capacity switching element in the ACI SPD has an overload detection which is always activated when mains follow current and thus a certain duration of current flows through the SPD arises.
Figure 14 schematically shows the ranges of significant (2) changes of MOV v/i characteristics up to short circuit (3) as well as the resulting protection ranges. Due to the specific ACI technology fault currents do not occur in mA or low A range (1).

When this overload detection is activated, the trigger circuit integrated in the switching element is deactivated. The SPD with deactivated trigger circuit is dimensioned so that the surge withstand capability of the combination of switching spark-gap and MOV is greater than the impulse withstand voltage of 4 kV required in overvoltage category III. The disconnection of the trigger circuit is irreversible and is signalled both by the integrated remote signalling contact and the status indicator.

Summary

The ACI technology presented here makes is possible, for the first time, to reliably protect MOV-based SPDs against all conceivable fault currents fed in from the mains. Here it is irrelevant whether the fault currents occurring are limited by the fault condition in the SPD itself or by the given network conditions. Whereas until now SPDs have been protected by OCPDs with time-dependent triggering characteristics, the overload

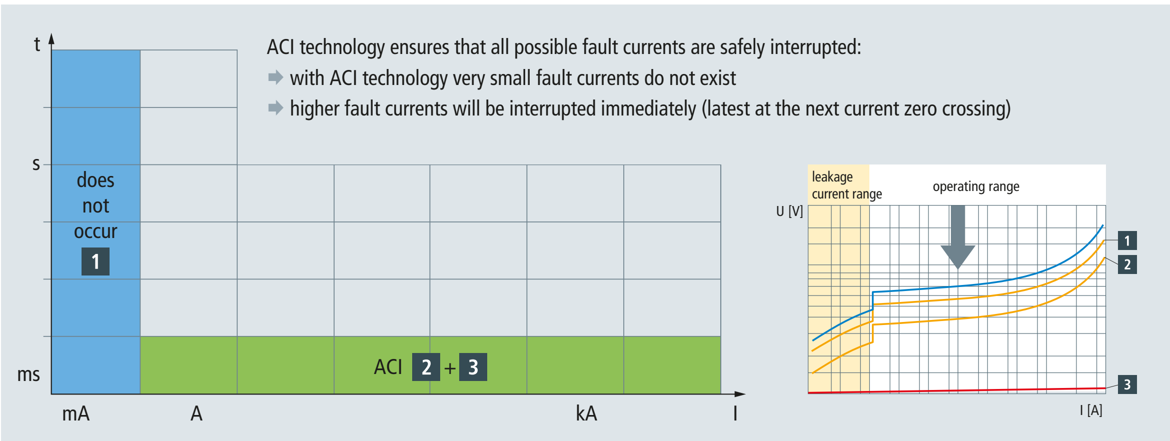


Figure 14 MOV characteristics and protection ranges of a type 2 SPD with ACI technology

protection of an SPD with ACI technology is immediate and without time delay.

The safe and reliable disconnection of the SPD from the mains is ensured, regardless of the installation location and the load status. The integrated overload detection makes it possible to register the overload situation, deactivate the SPD and report the failure.

Using ACI technology, SPDs can be used irrespective of the installation location, the network conditions and the type of network. Installation is simple and future-proof.

The overcurrent and short-circuit protection required for the SPD is already included in the integrated ACI technology. The small disconnection integral is selective to a 35 A gG fuse; no further OCPDs need to be considered.

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