SURGE PROTECTIVE DEVICES AND THE ALL-IMPORTANT "SPD DISCONNECTOR"

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Abstract: **Manufacturers of SPDs understand that their devices will eventually reach an end-of-life state, whether due to natural aging or due to conditions being imposed which are outside of normal operating conditions.**

International standards bodies such as the Electro Technical Commission (IEC) and Underwriters Laboratories Incorporated (UL) recognized the hazard posed by a failed SPD and include a number of tests in standards such as IEC 61643-12, IEC 62305-4 and UL 1449, to ensure that such devices fail in a safe manner. In order to comply with such standards, SPD manufacturers rely on "disconnectors". This paper introduces the importance of SPD "disconnectors" to the safe installation of an SPD and expands on aspects such as, internal versus external disconnectors and over-current versus thermal disconnectors. It also details the current methods used to evaluate the behaviour of disconnectors by these various standards setting bodies and the steps being taken to improve on these in new draft editions under development.

Keywords: **IEC, International Electro-technical Commission, NEC, National Electrical Code, UL, Underwriters Laboratories, SPD, Surge Protection, Disconnector, Short-Circuit Current Rating, SCCR.**

I. INTRODUCTION

An SPD by definition contains at least one nonlinear component which is intended to limit the surge voltage and divert the surge current. Inherent in the operation of such devices is the possibility of unexpected failure or rapid end-of-life. Under such conditions, it is important that the SPD can safely isolate itself from the prospective supply to which it is connected without presenting a potential fire hazard.

For this purpose a disconnector is usually incorporated, either in the housing of the SPD itself (internal disconnector), or as a separate component installed in the electrical network up-stream of the SPD (external disconnector).

The importance of such disconnectors to the safe operation of an SPD can not be over emphasized. It is for this reason that manufacturers put so much engineering effort into the careful design of disconnectors and standards committees, such as UL 1449 [2] and IEC 61643-1 [3], into the testing and evaluation of such devices.

This paper aims to introduce some of these more complicated aspects of both design and testing of disconnectors, and their coordination with the power distribution system to which they are connected. It also focuses attention on one of the more complicated areas where an SPD disconnector needs to operate – that of DC power systems which are being encountered more frequently as the use of photovoltaic panels and telepower distribution systems gain wider acceptance.

II. THE SPD DISCONNECTOR

A well designed SPD, or SPD installation, will generally require one or more disconnectors for safe isolation from the prospective current of the energizing supply during fault conditions. Without such, it is a potential fire hazard or explosion waiting to happen.

The failure mechanism of an SPD can generally be categorised as:

- A gradual end-of-life due to natural degradation (ageing) of the internal non-linear component(s) during normal operation, or
- A rapid end-of-life due to a catastrophic event outside the scope of the SPD's normal range of operation.

These two scenarios, by which an SPD can reach its end-of-life, generally place very different requirements on the disconnector(s).

Thermal disconnector - In the first case, where the failure is associated with a gradual degradation of the internal non-linear components (metal oxide varistors), a disconnector which is capable of sensing the thermal rise in temperature of the SPD is generally required. The objective being to isolate the failing varistor before it reaches thermal runaway and becomes a fire hazard.

Gradual degradation of the SPD can result from many causes, but most common amongst these are:

- Ageing of the metal oxide varistor (MOV).
- Sustained temporary overvoltages (TOV) of the power system, either due to poor system regulation (as in the case of long transmission lines), or when a multiphase system becomes unbalanced (as in the case of a loose neutral connection on US 120/240V systems).

Under such conditions, the rms current conducted by the SPD is usually limited to a few tens of amperes as it starts to enter conduction on the peaks of the sinusoidal supply, resulting in a progressive and gradual rise in temperature.

Over-current disconnector - In the case of the very rapid end-of-life (which can occur when an SPD is exposed to unanticipated events such as - a surge beyond its intended rating, or a large TOV as can occur when there is comingling of the HV and LV system) the disconnector must operate extremely fast in order to limit the energy of the prospective short-circuit current available from the supply to which it is connected. Under such conditions, a thermal disconnector would operate too slowly and the energy created in the failed SPD could result in a catastrophic explosion of the housing, and fire due to mains follow-current. To prevent this, an "over-current disconnector" such as a fast acting fuse or magnetic circuit breaker with well coordinated I2t characteristic, is required.

This need to include fast operating over-current disconnectors, has also meant that manufacturers need to grapple with a trade-off between fast isolation (high SCCR rating) and a low Imax (low maximum discharge current).

DC current disconnector – The growing interest in renewable energy generation has lead to a proliferation of photovoltaic panels in applications ranging from small residential installations to large commercial "sun farms". Such installations by their very nature are externally located and thus particularly subject to the effects of lightning induced damage. As a result, the use of SPDs on such panels is becoming increasing important and new standards such as [??]are being developed to address the testing and performance of SPDs intended for use on DC power systems. The disconnector in a DC-SPD needs to be designed in a very different way to that used in an AC-SPD. Not only does it often have to isolate much higher voltages (photovoltaic systems typically operate at 300, 600, 1000 VDC), but it also has to disconnect (open) when there is no zero crossing point to extinguish an arc as there would be on an AC system.

SPD manufacturers are only just starting to address these more onerous requirements. A number of innovative new disconnection designs have been developed and patented. Most of these use various mechanical shutters to extend the arc length while disconnecting, thereby cause self-extinguishing even though a voltage zero-crossing point is not present.

Figure 1: Patented technology developed by Iskra Zascite and incorporated into its Safetec product line of AC and DC SPDs uses "arc-lengthening" in its disconnector design, in conjunction with thermal current limiting components, to help control the follow-current while disconnecting on DC. The series meets IEC and UL standards.

III. TESTING OF SPD DISCONNECTORS

Two of the more important international surge protection standards are:

- Underwriters Laboratories Incorporated, ANSI/UL 1449 Edition 3, 2009 - Surge Protection Devices, and
- IEC 61643-1 Edition 2.0 2005 - Surge protective devices connected to low-voltage power distribution systems. Part 1: Requirements and tests.

UL1449 provides three tests to evaluate an SPD's ability to safely disconnect under simulated fault conditions[1].

UL Limited Current Test:

This test is intended to simulate a specific high impedance fault condition which is unique to the North American power system.

Many residential and light commercial installations in the US are fed with a 120/240V, 1Ph, 3W+G system derived from a centre-tapped transformer. This supply presents a particularly onerous set of problems to an SPD if it experiences the infamous "Loose Neutral" phenomenon – a problem which occurs if the neutral connection becomes corroded, or disconnected, and the loads connected between L1-N and L2-N are not balanced. Under such conditions, the zero point of the system shifts and the voltage on one "half" of the load will decrease, and that on the other "half" will increase. Under such conditions, the L-N voltage to which the SPD is connected may elevate above the nominal 120V and force the SPD into permanent conduction under a limiting current of several amperes.

[1] For more information on these simulated tests, please refer to the paper *"A Review of requirements governing the installation of Surge Protective Devices on the US Electrical Distribution Network"* by Surtees, Caie, Murko. Proceedings, International Conference on Lightning Protection (ICLP), 2006.

The test also serves to simulates the ageing behaviour of varistors as their Uc characteristics change and they begin to conduct (clamp) on the peaks of the 50/60 Hz supply sinusoid.

The test is performed by connecting the SPD to a current limiting supply set to 0.5, 2.5, 5 and 10A, with a "full phase voltage" (e.g. 240V for an SPD intended for use on a 120V 3W+G system, or 480V for an SPD intended for use on a 277/480V 4W+G system). This voltage is applied for 7 hours, or until the current to, or temperature of the SPD attains equilibrium, or until disconnection from the supply results. The SPD is required to pass safely – generally via the operation of the internal thermal disconnector.

UL Intermediate Current Test:

A well designed SPD will generally include both thermal and over-current disconnectors - the former being to take the SPD off-line during limited current situations when the failure occurs more gradually over time, and the latter being to rapidly disconnected before failure of the internal active elements can cause excess short-circuit currents to flow and induce a potentially catastrophic explosion of fire hazard.

Disconnection from currents of some hundreds of amps (intermediate currents) is generally difficult as both thermal and over-current disconnectors may be too slow to operate in this region. For AC-SPDs UL evaluates safe behaviour using: 100A, 500A and 1000A. The test protocol for DC-SPDs is currently under consideration, but it is likely that devices will be tested at: 10A, I_{SCPV} and 5 x I_{SCPV}, where I_{SCPV} is the prospective short circuit current of the photovoltaic panel it is rated for use with.

UL Short-Circuit Current Test:

This test evaluates the ability of an SPD to disconnect itself from a power system which is able to supply large prospective fault currents. The aim is to ensure that disconnection occurs sufficiently fast to limit excess energy in the failed SPD, thereby avoiding an explosion or fire hazard due to follow-currents. The test involves instantaneously applying an elevated voltage to the SPD from a supply capable of delivering the full short-circuit current which the manufacturer wishes to have marked on his product[2]. This simulates the race-condition which exists between the SPD's over-current disconnector (fuse or circuit breaker) and the build up of explosive energy in the failed internal non-linear component (MOVs, SADs, gaps etc).

Similarly, IEC 61643-1 evaluates an SPD's ability to safely disconnect using the following tests:

IEC Thermal Stability Test:

This test is similar to UL's limited current test in that it simulates the behaviour of the SPD when it reaches end-of-life due to ageing of its internal non-linear components. The test involves progressively increasing the current through the SPD in discrete steps of 2mA, and allowing thermal equilibrium to be achieved at each point before moving to the next increment. Under such conduction, the SPD gradually increases its internal temperature to the point where either safe disconnection, or burning, occurs.

IEC Temporary Over-Voltage TOV Test:

The TOV tests involve subjecting the SPD to various overvoltages which are intended to replicate those that can occur under various network faults. The SPD should either withstand, or safely disconnect, from these scenarios. The duration of time for which the TOV is applied is: 5s to simulate faults on the low voltage side of the distribution system and 200ms to simulate faults on the high voltage side (typical trip times of protection relays used on IEC regulated networks).[3]

IEC Short-Circuit Current Test:

IEC 61643-1 states that *"an overstressed (short-circuited) SPD shall withstand the power short-circuit currents which may occur in service"*. The testing entails sample preparation in which any voltage limiting components or voltage switching components are replaced by copper blocks (dummies). The modified sample is then connected to a power frequency source at the stated maximum operating voltage Uc and prospective short-circuit current Isc as declared by the manufacturer.

The modified sample is energised twice (once at 45 and once at 90 electrical degrees after the voltage zero crossing). If a replaceable internal or external disconnector operates it is replaced (or reset) and the test continued. Pass criteria is that there is no evidence of fire or burning.

IEC Intermediate Current Test:

To evaluate behaviour at low (intermediate) short-circuit currents, samples are again prepared with dummy copper blocks and energised at the maximum continuous operating voltage of the power system for five seconds[4]. The prospective short-circuit current is set to five times the rating of any up-stream over-current disconnector specified by the manufacturer (or 300 A if not specified). While this method has the right intention, detractors feel the method of replacing the active non-linear elements with shorting copper blocks limits its usefulness.

IV. COMPARING IEC AND UL TEST METHODS

From the preceding discussion, one can see that both UL and IEC go to some length to produce tests which will

[2] The National Electric Code [1] mandates that an SPD may not be connected at a point in the installation where it's marked short circuit current rating (SCCR) is lower than the prospective fault current at this location. The SPD manufacturer is only allowed to mark his product with the SCCR value tested under UL 1449. This is generally a value from 10kA to 200kA 60Hz.

[3] The TOV voltages and time durations used within IEC 61643-1 are often criticised as being inadequate to simulate the real life condition which SPDs installed on power networks outside of Europe may experience. IEC SC37A is currently requesting input from other National Committees as to what parameters are more applicable to these countries specific needs.

[4] Note: The maximum allowable time for fuse operation at five times the rated current is five seconds, for current limiting fuses in accordance with IEC standards.

simulate various fault conditions an SPD may encounter during its operation, and then to evaluate that the device is able to either withstand or disconnect from these in a safe manner.

Some have argued that the UL standard is probably more thorough in the area of safety testing than its IEC counterpart which arguably has a greater emphasis on performance testing. If there is any truth in this statement, it may be as a result of the different environments which SPDs encounter between IEC and ANSI based countries. For example, the issue of "loose neutrals" is more common to the 120/240V 3W+G single phase supply used in North American countries[5]. The US is also particularly aware of the risks which fire poses to its residential dwellings which are predominantly wood construction, rather than brick and mortar as is common to European countries.

Weakness in UL test methods:

The UL standard allows a manufacturer to adopt "containment" measures as a means to pass the various current tests described above (Section 39 in the standard). The only condition being that the usual pass criteria are met (e.g. tissue paper and cheese cloth must not burn and there must be no expulsion of molten material etc).

It is therefore possible for a product to fail to a short-circuit and have no series fuse or other over-current disconnector protection, provided its housing can withstand the energy associated, or internal fire created, until something isolates.

The problem with this is that there is no guarantee that the product will internally fail the same way in each case. By not requiring that a specific component be the current isolator (such as a fuse or thermal disconnect) is essentially allowing an uncontrolled behaviour. It is hard to argue with the logic that if the test were to be conducted at a different current, the uncontrolled internal failure would not violate (explode) the housing!

It is also troubling that certain measures UL require of manufacturers to ensure conformance in production, work unwittingly against the good intents of manufacturers to incorporate safe disconnect technologies into their products, and instead steer them down the arguably unsafe "containment" path.

For example, UL requires an SPD which includes a "non-recognised" disconnect to have this disconnect evaluated to a standard called UL 61691 (Ref. IEC 60691). This standard was designed to evaluate thermal-links, the small fuse-like components with set melting points which are utilised in a host of household electrical appliances to disconnect in the event of the temperature being exceeded.

The intention of this standard was never to evaluate the generally more robust thermo-mechanical disconnectors engineered into SPDs. As a result, the standard only has provision to evaluate the effective operation of such disconnects to a maximum short circuit current (SSC) of some hundreds of amps, while SPDs need to be rated with SCCRs equal or greater than that of the power system to which they will be connected – in most cases some tens of thousands of amperes.

Given this limitation – UL not only requires SPD manufacturers who incorporate such "non-recognised" disconnects in their products to test to this (inappropriate) UL 60691 standard, but also to pay for annual follow-up testing at the required SCCR. Such testing typically runs in excess of $50k – a large annual burden to any manufacturer.

If on the other hand, the manufacture does not include any sort of disconnect in his product, and simply relies on containment measures, it is not subject to any further testing provided the one sample passes.

There are elements here of UL trying to fit a square peg into a round hole (enforcing a SPD disconnects to go through an inappropriate standard), and not recognizing the excess burden they are placing on manufacturers (requiring annual follow up services) is steering SPD design to less than safe practice.

Weakness in IEC test methods:

One area where criticism of the IEC 61643-1 document is probably justified, is in the method of determining (and declaring) the short-circuit current withstand rating Isc of an SPD.

The IEC test method involves the replacement of the "active" components of the SPD with copper blocks (dummies). This creates an artificial situation which it is argued does little more than test the disconnector (external or internal) and internal connections, rather than meeting the requirement that "an overstressed SPD shall withstand the power short-circuit currents that may occur in service."

Furthermore, this test fails to evaluate one of the more acknowledged causes of SPD induced fire – that created when the active components catastrophically fail and in so doing, deposit semi-conductive metallization throughout the SPD, or cause internal conductive plasmas that can start follow-current arcing and burning.

It is important to understand that these active components are the main source of heat generation in the event of SPD failure (especially at intermediate current faults) and therefore the primary initiator of fires. Short-circuiting this component removes the potential heat source and leaves the IEC test method open to criticism.

It suffices to say that IEC SC37A/WG5, which is responsible for the development and maintenance of the standard IEC 61643-1, has established a task force to review the present test methods used to evaluate the disconnection of SPD's at end-of-life and during fault conditions. The difficulty faced by this task force is how to devise a more appropriate test which will evaluate the safe disconnection of a fail SPD while not creating artificially abnormal conditions to induce this behaviour in the first place!

[5] Note: on TT systems, it is possible for a loss of neutral connection to create a similar fault as can occur on the US 120/240V system.

V. SUMMARY

The importance of the SPD disconnector is fundamental to the safe isolation of an SPD during failure conditions. This paper has sought to address some of current test methods used to evaluate such disconnectors and noted the ongoing work to improve on this, in particular for DC applications.

In addition, the paper has attempted to highlight some of the deficiencies in both these standards - UL allows containment by the enclosure as a means of passing its sequence of current tests, which can lead to unpredictable and unrepeatable behaviour, while IEC allows substitution of the active elements of the SPD with a dummy copper block when conducting these short-circuit withstand test.

VI. REFERENCES

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