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SPDS – GRENADES WITHOUT PINS? COORDINATION OF AN SPD'S SHORT-CIRCUIT CURRENT RATING WITH THE SYSTEM TO WHICH IT IS CONNECTED

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***Abstract*: Much has been written on the subject of "SPD Coordination". References can be found in both manufacturer's literature and international standards such as IEC 61643-12 and IEC 62305-4. However treatment of the subject is generally limited to a treatise on the coordination of one SPD with another, or one SPD with the equipment to be protected, where the principal objective is to ensure proper current sharing during surge conditions. In itself, this is an important and often non-trivial exercise, particularly when the SPD's comprise different topologies, such as voltage switching (spark gaps) and voltage limiting (metal oxide varistors). However of more importance, since it relates to safety, is the coordination of an SPD's short-circuit current rating with the prospective current of the network at the point of intended installation.**

The aim of this paper is to address this little understood aspect of SPD selection and coordination, and highlight its importance to the correct operation of an SPD during surge conditions and its safe disconnection during device failure.

The paper will introduce the importance of SPD "disconnectors" to the safe installation of an SPD and expand on aspects such as internal versus external disconnectors and over-current versus thermal disconnectors. It will also cover Code and Listing requirements in the USA requiring an SPD to be tested and marked with a short-circuit current rating and the manner in which this is evaluated per national test standards such as Underwriters Laboratories Incorporated, (UL), and international standards such as IEC 61643-1. It will also discuss some of the short falls with these test methods and steps being taken to improve on these in new draft editions under development.

Finally, the paper will review the behaviour of an SPD under conditions of low and intermediate short-circuit currents (related to high impedance failure modes) and will discuss proposed tests to evaluate safe disconnection under this common type of failure.

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

1 INTRODUCTION

An SPD, by definition, is a device containing at least one nonlinear component, the purpose of which is to limit surge voltages and divert surge currents. 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 in the installation of an SPD. This disconnector may either be integrated into the housing of the SPD (internal disconnector), or may be a separate component which is installed up-stream of the SPD during installation (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 seeks to address some of these more complicated aspects of both design and testing of disconnectors, and their coordination with the overall power distribution system to which they are connected during normal installation and operation.

2 SPD DISCONNECTORS

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 – a grenade without a safety pin!

The scope of eventualities which the disconnector(s) must protect against can generally be categorised into two camps:

- Gradual end-of-life of the SPD due to natural degradation (ageing) of the internal non-linear component(s) during normal operation, and
- 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 require very different behaviour of the disconnector(s).

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 as it starts to conduct current on the peaks of the sinusoidal supply, is generally required. The objective being for this "thermal disconnector" to isolate the failing varistor before it reaches thermal runaway and becomes a fire hazard.

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 temporary over voltage TOV of the power 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. A thermal disconnector would under such conditions 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 with well coordinated I^2t characteristic, is generally required.

3 SAFETY STANDARDS – TESTING OF SPD DISCONNECTORS

The importance of safe disconnection of a failing SPD is recognized in many national and international standards on surge protection. Two of the most important being:

- Underwriters Laboratories Incorporated, ANSI/UL 1449 Edition 3, 2006 - Surge Protection Devices, and
- IEC 61643-1 Edition 1.1 2002 - Surge protective devices connected to low-voltage power distribution systems. Part 1: Performance requirements and testing methods.

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

Limited Current Test:

This test simulates a potential high impedance fault condition which can occur on a typical 120/240V North American power system if the Neutral conductor becomes disconnected or the connection corroded. 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. The test also simulates the end-of-life behaviour when an SPD ages and the internal varistors components change their characteristics (U_c) and begin to clamp on the peaks of the 50/60 Hz supply sinusoid.

UL simulates this failure mechanism by connecting the SPD to a current limiting supply set to 0.5, 2.5, 5 and 10A in turn 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 attain equilibrium, or until the SPD becomes disconnected from the supply. The SPD is required to pass safely – generally via the operation of an internal thermal disconnector.

Intermediate Current Test:

This test is considered by SPD manufacturers as one of the more difficult tests to design for. As already stated, a well designed SPD will generally include both thermal and over-current disconnectors - the former being to take the SPD

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[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.

off-line during limited current situations when the I^2R heating due to a failing internal component, allows watts of heat to slowly build within the device, and the latter being suitable when very fast disconnection is needed to avoid catastrophic failure of the internal active elements of the SPD under conditions of high short-circuit currents.

The disconnection under 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. UL now tests safe operation at intermediate currents of 100A, 500A and 1000A. The intention as always being to ensure safer products in the market.

Short-Circuit Current Test:

This test evaluates the ability of an SPD to disconnect itself from a power system sufficiently quickly to avoid explosions and burning 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).

In a similar manner, IEC 61643-1 evaluates the SPD's disconnector(s) using three main tests:

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 gradually increasing the current through the SPD in discrete steps of 2mA, allowing thermal equilibrium to be achieved at each point before moving to the next increment. This current causes the SPD to gradually increase its internal temperature to the point where either safe disconnection, or burning, results.

Temporary Over-Voltage TOV Test:

In this, the SPD is subjected to various voltages similar to what the power system may present to it 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]

Short-Circuit Current Test:

IEC 61643-1 requires that *"an overstressed (short-circuited) SPD shall withstand the power short-circuit currents which may occur in service"*. Testing to determine this involves preparing a modified sample of the SPD in which any voltage limiting components or voltage switching components are replaced by copper blocks (dummies). The sample is then connected to a power frequency source at the stated maximum operating voltage Uc, with 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.

4 COMPARATIVE EVALUATION OF IEC AND UL TEST METHODS USED TO ENSURE SAFE SPD OPERATION

From the preceding discussion, one can see that both UL and IEC go to great lengths to produce tests which will simulate various fault conditions which 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

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[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.

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[4]. The US is also particularly aware of the risks which fire poses to its residential dwellings which are most often of wood construction, rather than bricks and mortar.

Problems with current methods used to evaluate the short-circuit behaviour of an SPD and to determine its rating:

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

As we have seen, the present 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 most 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.

On the other hand, the UL method of subjecting an SPD to an elevated voltage in order to force instantaneous failure of the active component - and thereby ensuring the prospective fault current of the supply will flow - is also artificial in that the voltage required to initiate this failure may be in excess of what the network can produce in reality. It is worth noting that UL does allow a manufacturer certain exceptions if he wishes to perform this test at the nominal rated voltage of the SPD:

- The internal conductive elements of the SPD may be replaced by those of lower voltage which will ensure rapid conduction and destruction of the sample on energizing at rated voltage.
- Any voltage switching components in series with voltage limiting components may be short-circuited to facilitate conduction at a lower voltage than would normally be required.

The prime focus of UL in determining an SPD's short-circuit current rating (SCCR in US nomenclature), is to force the device into hard conduction where it will exhibit its ability to disconnect from such a source in the event of failure. While this approach may appear somewhat artificial, it does explore the over-current disconnector's ability to limit the short-circuit current to the device before the energy content reaches catastrophic levels. It also meets another important objective in any test in that it can be readily reproduced and does not require any special sample preparation (tampering).

The IEC method on the other hand, only really evaluates the disconnector's ability to isolate a short-circuit (dummy copper block) as well as aspects of the mechanical construction, such as the terminals and inter-connections, which are subjected to the full short-circuit current.

The need to also evaluate an SPD's disconnector(s) at "intermediate currents":

Data collected by the US Product Safety Commission, caused UL to introduce additional testing under so called "intermediate currents" during the later stages of UL 1449 Edition 2.

The commission found that there were cases where an SPD could be shown to safely disconnect under limited current faults (thermal disconnection) as well as high short-circuit current faults (over-current disconnection), but in between these two extremes there existed a window where the internal active components of the SPD could be shown to generate enough heat to initiate fire before disconnection had taken place.

To better evaluate this region, tests using intermediate currents as 100, 500 and 1000A were introduced by UL. The test method is essentially identical to that used in the short-circuit current tests.

Similarly, IEC 61643-1 includes a test to evaluate behaviour at low (intermediate) short-circuit currents. The test again uses SPD samples prepared with dummy copper blocks and applies a prospective short-circuit current equal to

[4] 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.

five times the rating of any up-stream over-current disconnector specified by the manufacturer (or 300 A if not specified), and energised at the maximum continuous operating voltage of the power system for a duration of five seconds. Note: For current limiting fuses in accordance with IEC standards, five seconds is the maximum allowed time for fuse operation at five times the rated current. 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.

The IEC response:

To assess the concerns being expressed by certain national committees, 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! In addition, it is desirable to have a test which is reproducible and yet does not rely for this purpose on undue modification of the sample. It is expected that the next Committee Draft (CD) of this standard (IEC 61643-11 Ed. 1.0) which will circulate towards the end of this year, will contain revisions to the present short-circuit withstand test, and likely the inclusion of testing at intermediate currents – similar to those adopted by UL.

Problems and loop holes in ANSI/UL 1449:

The introduction of Ed 3 to UL1449, which was first issued in August 1985, has sought to address many concerns of both manufacturers and users[5] and in general should be complimented for leading to safer products. There are however a few areas in the authors' views where there is room for improvement. One particular concern is that UL allows for "containment" as a means of passing the various current tests of Section 39. 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 allowance 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. What is to say that if the test were to be conducted at a different current, the uncontrolled internal failure would not violate (explode) the housing?

5 THE NEED FOR AN SPD'S SHORT-CIRCUIT CURRENT RATING - REGULATIONS GOVERNING THE INSTALLATION OF SPDs

Much has been said about the need for an appropriate test regimen by which the short-circuit withstand rating I_{scw} of an SPD can be assessed, but why is this important and where is it used? To answer this, a few words are needed to put into context the regulations governing the installation of SPDs.

IEC 60364, *Electrical installations of buildings - Part 5: Selection and erection of electrical equipment - Clause 534: Devices for protection against overvoltages*, deals with the installation of SPDs in IEC compliant installations. Within this document there is a section which deals with the coordination of an SPD's short-circuit current rating with the available current at the point of installation. It states:

"The short-circuit withstand of the SPDs (in case of SPD failure) and the follow current interrupt rating, shall be equal to or higher than the maximum short-circuit current expected at the point of installation…"

Similarly within the USA, Article 285.6 of the National Electrical Code[6] states:

"An SPD shall be marked with a short-circuit current rating and shall not be installed at a point on the system where the available fault current is in excess of that rating."

Whilst this commonality of intention is encouraging, the regulatory requirements which govern its enactment are

[5] For more information on these simulated tests, please refer to the paper "*A review of the current test methodologies for surge protective devices - a comparison of IEC and UL test methods*" by Surtees, Bachl, Rousseau. Proceedings, International Conference on Lightning Protection (ICLP), 2006.

[6] The National Electric Code (NEC®) [1] is the primary authority in the USA (and some North American countries) which regulates equipment allowed to be connected to the utility power system (electrical network). It is administered by the National Fire Protection Association under NFPA 70. The code is revised on a 3 year *code revision cycle*, 2008 being the current edition in effect.

often quite different between the USA and other IEC adopting countries. In the USA, it is mandatory that the National Electrical Code be followed (with few exceptions)[7] and that an SPD be "*Listed for its purpose*"[8]. This in turn requires compliance with UL 1449, making the short-circuit current rating which UL assigns to an SPD a critical aspect governing where it may be installed[9].

In addition, UL508A[10] which covers listed industrial control panels, details marking requirements for the SCCR of a panel board. New requirements within the US per Article 409, requires that the entire panel and all components inside meets a defined Short-Circuit Current Rating (SCCR) for the application[11]. The panel must be marked with this SCCR together with any conditions of acceptability for the location (i.e. use of additional series fuse).

These new marking requirements make it possible to correctly select an SPD for the panel to which it is to be connected.

For example, an SPD with a 25kA SCCR may not be installed on a panel board of 100kA SCCR. Note: a possible exemption to this is allowed if additional, and suitably rated current limiting fuses are installed.

The situation with IEC adopting countries is rather less regulated in that a contractor in some countries may install an SPD even if it does not complying with IEC standards and even if the country is a signatory to the IEC. Essentially, enforcement of IEC standards is more an issue of national legislation or electrical codes and is usually addressed on a country-by-country basis.

This is not the case at CENELEC levels where European norms such as EN 61643-11, apply and are mandated under the low voltage directives (aspects of this "mandatory" situation are still not fully enacted). This said, it is also important to realize that EN 61643-12 (the application guide which addresses installation requirements) is not listed in the low voltage directive. This creates a loop hole in which it is possible to have an installation of, SPD plus disconnector, which complies with all necessary directives, but does not meet the conditions of use tested under EN 61643-11.

One glaring difference between IEC and UL is exposed here – UL write and test to their standards and third-party testing is compulsory in order to mark (List) and sell a product in the USA. IEC on the other hand is only a standards creating organization, and does not test or regulate testing to its standards. Manufacturers in Europe are generally allowed to self-certify to such standards and apply the CE mark by themselves[12]. In other words, an honesty basis is relied upon, which is a questionable practice when personnel safety is at stake. One may question whether manufacturers are truly testing the SCCR markings being assigned to SPDs in Europe, and whether there are strong enough enforceable regulations governing their coordination with panel boards in which they are installed[13].

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

[8] Note: NEC Article 285.3 prohibits the installation of an SPD on circuits that exceed 1000 volts, or circuits where the rating of the TVSS is less than the maximum continuous phase-to ground power frequency voltage available at the point of application and on ungrounded systems, impedance grounded systems or corner-grounded delta systems unless the SPD is specifically Listed for use on these systems. SPDs are specifically required to be Listed in NEC Article 285.5.

[9] Note: UL requires that an SPD be marked with the following: "A permanently-connected (other than receptacle type) SPD, shall be marked: *Suitable for use on a circuit capable of delivering not more than x rms symmetrical Amperes"*.

[10] Article 409 on Industrial Control Panels was added to the NEC in the 2005 edition. This Article requires all Industrial Control Panels to be marked with a Short Circuit Current Rating. The Short Circuit Current Rating (SCCR) requirements for UL 508A took effect in April 2006.

[11] Section 409.110 requires a Short Circuit Current Rating (SCCR) to be marked on an Industrial Control Panel. It notes the rating is to be based on the rating of a listed and labelled assembly or an approved method to establish the rating. It also includes a Fine Print Note (FPN) reference to UL 508A Supplement SB as an example of an approved method for determining the SCCR that can be marked on the panel.

[12] The National French (NF) mark requires that third party testing be conducted and the independent watch dog organization DGCCRF monitors the market for compliance and has the authority to have products which do not meet these requirements removed.

[13] Note: There is no Cenelec standard which requires panel boards to be marked with a short circuit current rating, as there is in the US. This can make the correct installation and coordination of SPDs more difficult.

6 DISCONNECTORS ISSUES AND TRADE-OFFS

As stated earlier, a race-condition will exists between the over-current protection operating and the energy being dissipated in the failed SPD. Careful selection and coordination is needed to limit this energy to avoid the hazards of fire or explosion. In practice, such over-current protection may be provided by an external backup fuse or circuit breaker. Some SPD's may even make this protection integral to the design. In the US, a Type 1 SPD per UL 1449 nomenclature, is one intended for use on the line side of the main panel-board and is required to include its own over-current disconnection.

Obviously, the faster the operation of the over-current device, the less likely that catastrophic failure of the SPD will occur. In general, this requirement necessitates that the fuse have a fast acting melting element. Unfortunately, this also limits its ability to handle large surges and unwanted tripping or melting can occur.

It is possible to obtain an approximate of the single shot withstand rating of a fuse, by comparing the I^2t of the surge waveshape to that typically provided by fuse manufacturers for a 1ms pulse.

The I^2t rating of a surge of specified waveshape with peak value I_{crest} can be approximated using the following [4]:

- 8/20 wave shape: $I^2t = 14.01 \times I_{crest}2$ (1)
- 10/350 wave shape: $I^2t = 256.3 \times I_{crest}2$ (2)

where: I_{crest} is given in kA, and I^2t in A^2s

From the above formulae we note that, to withstand a 9kA 8/20 single shot surge, a fuse must have a minimum pre-arcing value of 1135A^2s. From fuse manufacturer's data we find that a 32A cylindrical gG fuse provides a typical pre-arcing value of 1300A^2s, which is close.

Likewise, to withstand a 5kA 10/350 single shot surge it must have a minimum pre-arcing value of 6407A^2s, which is close to that offered by a typical 63A NH gG fuse type. Table 1 shows the relationship between fuse ratings and surge ratings for one single shot of the waveform 8/20 or 10/350, and for the condition where the full operating duty test of IEC 61643-1 needs to be met[14].

So where is the reality in practice? Laboratory experience gained in testing a number of different SPDs to UL 1449, shows that safe disconnection it is not easily obtained under the intermediate current test regimen with fuses in excess of 30A minimum breaking current (US J class).

Using equation (1) above and fuse manufacturer's data, we find this equates to a surge rating of approximately 9kA 8/20. Unfortunately, the 'horse power race' which has manufacturers seeking to market SPDs with higher, and higher, surge ratings of both I_{max} and I_{imp} often overlooks the limitations which the upstream disconnects impose on this parameter.

The new requirements under UL1449 where both testing to the manufacturer's claimed SCCR and requirements that these ratings now be marked on the SPD[15], are helping to curtail the once excessive claims of surge ratings made by manufacturers. It is also forcing on the industry a new awareness of the importance in the careful selection of the over-current disconnector. Indeed today, most SPD manufacturers in the US strive to select an appropriate disconnector which will first, ensure safe behaviour (and passing of the UL intermediate and short-circuit current test protocols) and second, will achieve a desired surge rating – a reversal of past practice. UL has also sought to further enforce this priority towards safety by not providing any test for claims of I_{max} or I_{imp} in favour of only providing a test for the nominal discharge current I_n at 15 surges which the disconnector must withstand without operation.

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[14] IEC 61643-1 details a test regimen in which a sequence of preconditioning and operating duty cycle is applied - and the disconnector is not allowed to operate. During this test sequence of up to 15 impulses of the nominal discharge current I_n, the disconnector (fuse) deteriorates and will only withstand a small value of I_{crest} after such conditioning.

[15] A permanently-connected one-port or two-port SPD requiring an external fuse or circuit breaker shall be marked in accordance with 64.11 and, in conjunction with that marking shall also be marked:

*"When Protected by: *a Class Fuses"* and/or *"When protected by a circuit breaker rated: *b maximum and minimum *c Volts"*.

where:
*a - Class CC, CD, G, H, J, L, R, T or K fuse. Reference to Class H or Class K fuses shall not appear in the marking if the indicated rms symmetrical fault current is greater than 10,000 A.
*b - Current rating of circuit breaker.
*c - Nominal system voltage.

Fuse rated current Amperes	Cyl gG				NH gG			
	Pre-arcing A²s	Calculated withstand One shot only	Tested withstand Operating duty	Ratio	Pre-arcing A²s	Calculated withstand - one shot	Tested withstand - operating duty	Ratio
	I²t	8/20	8/20		I²t	10/350	10/350	
25	800	7.6	5	0.66				
32	1300	9.6	7	0.73				
40	2500	13.4	10	0.75				
50	4200	17.3	15	0.87				
63	7500	23.1	17	0.73				
80	14500	32.2	25	0.78				
100	24000	41.4	30	0.72	20000	8.8	5	0.57
125	40000	53.4	40	0.75	33000	11.3	7	0.62
160					60000	15.30	10	0.65
200					100000	19.75	15	0.76
250					200000	27.93	20	0.72
315					300000	34.21	25	0.73

Table 1 [4] - Typical surge ratings of different fuses when required to withstand one single shot, and when required to withstand the full operating duty cycle test regime of IEC61643-1

7 PRACTICAL ISSUES OF DISCONNECTOR COORDINATION

European distribution networks generally have very much lower short-circuit current ratings than those of North America. This can present a special set of problems when trying to achieve safe installation coordination using over-current disconnectors while at the same time trying to ensure that the SPD's surge rating is not adversely limited.

Scenario 1- Correct coordination of I_{sc} but not of I_{max}:

Take the example of a typical residential installation where the prospective short-circuit current may be as low as 1kA. Typically the installer will protect such an installation with a 63A fuse (15 times less than the prospective short-circuit current). If an SPD rated I_{max} 40kA is installed after this disconnector and the manufacturer specifies backup protection of 120A or less is required, then according to IEC 60364, one may omit this 120A fuse and rely solely on the 63A system fuse. Unfortunately, we see from Table 1 that a 63A fuse will only withstand approx. 23kA 8/20. In other words, the installation has achieved short-circuit current coordination, but not surge current coordination. In practice this means that a single surge of greater than 23kA may blow the 63A system fuse (upstream of the SPD), and remove power to the entire installation. For this reason, it is recommended practice in France (and in accordance with IEC 61643-12) that SPDs be protected on the branch circuit to which they are connected by a fuse of lower rating than the main system fuse (32A in this case). An SPD which incorporates such over-current disconnection[16] as integral and internal to its enclosure (designated a Type 1 SPD per UL 1449 Ed3), both achieves this objective and provides convenience of installation to the contractor since no additional external fuses or circuit breakers need be installed. In the event of a surge event beyond its rating, the internal protection will serve to isolate the SPD without removing supply to downstream equipment.

Scenario II - Incorrect coordination of I_{imp} on networks with low prospective short-circuit currents:

In this scenario we consider an SPD test class I connected to a typical residential installation where the prospective short-circuit current is again 1kA. In order to withstand I_{imp} 25kA, the manufacturer specifies a backup fuse of 315A be used. Under such an installation, the melting element of a 315A fuse will typically take > 30s to operate if a fault occurs on the SPD (assuming a perfect short circuit).

Under the present IEC 61643-1 short-circuit withstand test using the dummy copper block, it may be possible to withstand this event, but in real life where the SPD's active element is subjected to this prolonged current, fire will almost certainly occur before disconnection.

The only way for such an installation to achieve safety, is for the backup fuse to be reduced to suit the installation

[16] Such over-current protection may be a fuse or a circuit breaker, however fuses generally react faster and so are more suitable and most often used when a high short circuit current cordination needs to be achieved.

(i.e. to use a 63A fuse), and to accept that the surge rating of the SPD installation will not actually withstand I_{imp} 25kA without causing operation of the fuse and the need for replacement[17].

It is disturbing that new standards such as IEC 62305-4 [6] advocate the selection of SPDs for lightning protection installations based solely on aspects such as: lightning current sharing models, surge ratings and test class, while paying no regard to the safety and importance of short-circuit coordination of these parameters with the prospective current of the network and the type of back-up protection required.

8 SUMMARY

This paper has sought to highlight the importance of the SPD disconnector in ensuring safe isolation of an SPD during failure conditions. It has highlighted the need for both thermal and over-current disconnection to meet the aging and catastrophic failure modes associated with an SPD. It has discussed the importance of coordinating the SPD's short-circuit current rating with the prospective current of the network at the point of installation, as well as test methods in IEC and UL standards to determine this rating.

In addition, there has been an attempt to highlight some of the deficiencies in both these standards in dealing with the determination of this rating. In particular, UL1449 Ed3 allows containment by the enclosure as a means of passing its sequence of current tests, which can lead to unpredictable and unrepeatable behaviour. On the other hand IEC 61643-1 allows substitution of the active elements of the SPD with a dummy copper block when conducting these short-circuit withstand test, thereby removing the potential heat source from the test and thereby limiting its effectiveness to simulate actual field failures. This approach can also masks potential problems which can result from the dispersion of semi-conductive contaminants within the failed SPD housing - such as changing the nature of a simple L-G fault to one of phase-to-phase or three-phase to ground.

UL 1449 acknowledges that so called intermediate currents – those above the limited currents of the thermal stability test and the high currents of the short-circuit current test – are often a major cause of SPD initiated fires, and has an extensive test regimen to evaluate the SPD's ability to isolate itself under these conditions. The present tests of IEC61643-1 are arguably deficient in this area, and the subject of review under a committee draft to circulate this year.

Finally, the paper has sought to educate that safe (correct) coordination of an SPD's SCCR with the prospective current of the network, may mean that the SPD's declared surge rating (Iimp / Imax) may not be obtained, and that more work is needed in standards such as IEC 62305-4 and IEC 61643-12 to explain this trade-off.

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10 REFERENCES

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[3] IEC 61643-12: International Electro-technical Commission, *Low-voltage surge protective devices – Part 12: Surge protective devices connected to low-voltage power distribution systems – Selection and Application Principles*.

[4] IEC SC37A/WG3 TF submission: V. Crevenat, ABB – *Surge rating for fuses and transient responses*.

[5] IEC 62305-4 Ed 1.0: International Electro-technical Commission, *Lightning Protection – Part 1: Protection of Electrical and Electronic Systems.*

[17] It should be noted that even though the 63A fuse can only withstand approximately I_{imp} 5kA before operating, the SPD will actually "experience" (divert) the fully surge current of much greater value and thereby protect the equipment. This is because the surge is in the microsecond time domain, while the I^2t melting properties of the fuse are in the millisecond time domain!