Black boxes, blind spots, and disconnectors: How not to test SPDs

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Significance
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The current standards for testing SPDs, in particular their behavior in the face of temporary overvoltages and resultant failure modes leave some ambiguities for their implementation. Field failure data show that some SPDs that pass standard tests can still fail in unacceptable or unexpected modes, perhaps because of “blind spots” in the test regimen. The paper shows by case histories some examples of such unresolved issues and also suggests closer attention to the disconnector function, going as far as recommending that the disconnector function should be a mandated part of the SPD application considerations, possibly integral with the SPD package.

BLACK BOXES, BLIND SPOTS, AND DISCONNECTORS: How not to test SPDs

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Abstract — The current standards for testing surge-protective devices (SPDs), leave some ambiguities for their implementation. Field failure data show that some SPDs that pass standard tests can still fail in unacceptable or unexpected modes, perhaps because of "blind spots" in the test regimen. The paper shows examples of such unresolved issues and also suggests closer attention to the disconnector function.

1. INTRODUCTION

A long-standing philosophy, perhaps even a doctrine, in the approach to testing surge-protective devices (SPDs) is that test specimens should be seen as "black boxes" – meaning that all brands of devices should be treated alike, regardless of their internal design. Such an approach is commendable for the sake of "fairness" and is understandably motivated by concerns that a testing organization should not manipulate its test regimen to produce results that would favor one particular design while deprecating another design.

Meanwhile, given the practical limitations of testing a "reasonable" number of specimens over the wide range of possible stress threats, some test standards attempt to specify only a limited number of stress levels that appear "realistic," but which can leave blind spots in characterizing the performance of the device.

This situation is not just an intellectual concept; this paper presents examples of field failures or laboratory tests that occur for stress conditions that were not identified in the test regimen recommended or mandated by the current relevant product standard(s).

2. BLACK BOXES

A brief perusal of existing IEEE definitions should facilitate the discussions, avoid confusion, and ensure common understanding of the terms:

black box – A system or component whose inputs, outputs and general function are known but whose contents or implementation are unknown or irrelevant. ***Contrast: glass box.***

blind spot – A limited range within the total domain of application of a device, generally inferior to the maximum rating. Operation of the equipment or of the protective device might fail in that limited range despite demonstration of satisfactory device performance at maximum ratings.

functional testing – Testing that ignores the internal mechanism of a system or component and focuses solely on the outputs generated in response to selected inputs and execution conditions. ***Synonym:*** black-box testing.

glass box – A system or component whose internal components or implementation are known. Synonym: white box. ***Contrast: black box.***

white box – ***See: glass box.***

3. BLIND SPOTS

3.1 Terminology

The term "blind spot" in the context of SPD testing first appeared in IEEE Std C62.45™-1987 [1] as the authors of that document were keenly aware of the possibility that for some intermediate stress conditions, the SPD might not perform as expected, in spite of demonstrated satisfactory operation at maximum stress. One long-standing definition of that term, which appears in Webster's as "*An area in which one fails to exercise understanding, judgment, or discrimination,*" provides a good perspective to the context of surge testing: a lack of understanding how the device works (as in black-box testing) can indeed lead to not recognizing blind spots in the domain of application of the SPD. Supporting the skepticism about black-box testing philosophy, Webster's also mentions that lack of judgment (here an unquestioned application of blanket procedures) can also lead to blind spots.

This term of blind spot is now being extended to the arena of testing, not just for performance of the protective function, but also for failure mode testing. If a test regimen fails to ferret out a region where an unacceptable failure mode can occur, we now say that there is a "blind spot" in that test regimen, thus implying a secondary definition of that term.

Blind spots in surge-protective devices, the general subject of this paper, generally result from the transition of operation among internal components that respond in a different manner, depending on the parameters of the applied stress. An example of blind spot in the SPD performance can occur in the transition of operation from a voltage-limiting device to a voltage-switching device (in the same package or in a combination of two separate packages). An example of blind spot in the test regimen is the occurrence of an unacceptable failure mode at the transition from a fast-acting to a slow-acting overcurrent disconnector, allowing higher energy deposition during a mid-range fault that endures, compared to the potentially higher energy deposition for a large fault but which is promptly cleared by the SPD disconnector.

With knowledge of the principle of operation of the SPD, as well as details on the component characteristics, a test laboratory and the agency requesting the tests have a much greater likelihood of successfully anticipating where in the range of possible stresses a test blind spot might occur, and therefore focus on that range of stress.

In a non-adversarial test program, the manufacturer is also in a good position to share the experience gained in the design stages and thus offer recommendations to the laboratory for test levels that would indeed focus on the crucial parts of the range where transitions might occur between the operation of one internal component to another. During the design stages, a manufacturer can be expected to thoroughly explore the range of stresses to which an SPD might be exposed, and make the appropriate design adjustments to prevent the occurrence of a blind spot, which might otherwise have been overlooked if only the test regimen mandated by the present standards had been applied.

3.2 The quest for blind spots

As a result of the two meanings of "blind spot" we need to differentiate between the two:

- A blind spot in the surge-protective function;
- A blind spot in the demonstration(s) of acceptable failure modes.

Blind spots in the protective function have by now been recognized and are not the subject of much debate. For instance, the protective function of a hybrid SPD that includes a voltage-switching device, a decoupling inductance, and a voltage-limiting device might not work at some intermediate ranges of surge current, or with slow rising surges because the inductive drop expected from the decoupling inductance is insufficient to sparkover the voltage-switching device.

As this type of test is nondestructive, it can be easily repeated on the same specimen over the wide range (matrix) of waveforms and amplitude levels. Hence, the phenomenon is well recognized and has been described at some length in the IEEE Recommended Practice on Surge Testing [1].

In recent years, recognition of temporary overvoltages (TOV) as the most likely cause of SPD failures, rather than excessive surges, has considerably increased. This recognition is quite apparent in the inclusion of guidance on the occurrence of TOVs for recent standards whose primary scope is describing the occurrence of surges (and thus were expected by some members to exclude consideration of TOV issues), for instance IEEE C62.41.1™-2002 [2]; IEC 62066:2002 [3], and UIE Guide Part VI-2001 [4]). However, these new standards do not include much guidance on testing the performance of SPDs under TOV conditions. To be meaningful and realistic, a test scenario intended to produce failure of the test specimen under such a TOV condition must stipulate a well-defined level of the available fault current to be delivered by the power distribution system to the failed specimen.

That is where the issue of blind spots in the test regimen, and blind spots in the performance of the disconnector (if any) becomes the subject of the present debate in the intense quest for selecting suitable available fault current values that have a chance of ferreting out the blind spots in what might otherwise appear to be reassuring set of acceptable failure mode demonstrations.

Some SPDs returned from the field as in-service failures have an appearance quite different from that obtained by laboratory testing under TOV conditions suggested or mandated by the present SPD standards. Examples of such discrepancies are given later in this paper. Such a discrepancy then raises the old question of how a test regimen is expected to "duplicate" field conditions by "realistic" testing, or whether a test should be performed on the basis of arbitrarily (but still intelligently) stipulated stresses. This problem has caused, and still causes intense debates in the field of surge testing: waveforms and amplitudes have been set in standards by a consensus process based sometimes on very limited field data.

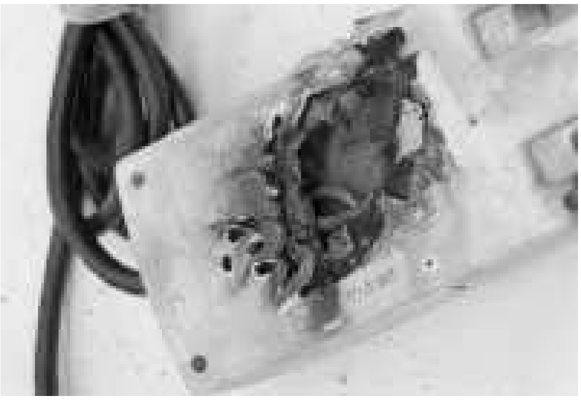
An example of that debate occurred in the development of the so-called "SPD Trilogy" [1], [2], [5]. when addressing the case of a direct lightning flash to the building of interest A similar debate has now emerged on the subject of realistic TOV testing – with the added complication that the position of blind spots within the range of available fault currents is presently more a matter of consensus than of hard facts.

4. EXAMPLES OF BLIND SPOTS

The following nine photographs showing examples of failure modes of cord-connected or hard-wired SPDs, (communicated to me as anecdotal information for the purposes of this paper) illustrate the concerns about blind spots in earlier as well as in the present standardized test procedures. Five of these examples deal with consumer-type plug-in or cord-connected SPDs, the other four with hard-wired SPDs. These four sources of data are gratefully acknowledged for providing me with real-world examples, but please note that I have no intention to pin blame on a particular product, only to illustrate that the problem is real. For this reason, the photographs of the cord-commected SPDs shown here were selected from many available ones, so as not to be readily identifiable as a particular brand.

4.1 Blind spots in performance and testing of cord-connected SPDs – EPRI PEAC tests

Figure 1a shows an example of a UL-listed SPD (UL 1449 First Edition) [6] that failed in the field with an unacceptable manner after exposure to a TOV caused by loss of the neutral connection. The available fault current at that site was not known. Figure 1b shows an example of TOV failure induced in the laboratory during exposure to 170 % of normal voltage (a typical lost-neutral scenario) with an available fault current of 10 A – a level that would not trip a typical 15 A breaker.



(a)

(b)

Figure 1 – Examples of TOV-induced failure modes on SPDs listed per UL 1449 First Edition
(Courtesy EPRI PEAC Corporation)

Growing awareness of this type of failure mode was one of the motivations for the development of the Second Edition of UL 1449 that now includes a regimen of tests with a stipulated range of limited available fault currents for abnormal voltage conditions.

As a result of the new edition of UL 1449, some design changes were made in existing products that were found in laboratory tests to fail the new requirements. Figure 2a shows an example of a pre-1449 Second Edition SPD that failed in an unacceptable manner when subjected to the new limited-current test per UL 1449 Second Edition. Figure 2b shows the same but redesigned SPD model in which the addition of a thermal cut-out made the failure mode acceptable. Thus, evolution of UL 1449 into specifying additional available fault current values did prove to be effective in enhancing the product safety, but there are still some blind spots in some 2002-vintage SPDs, as Figure 3 will show.

(a) Before redesign

(b) After redesign

Figure 2 – Failure modes before and after redesign
(Courtesy EPRI PEAC Corporation)

4.2 Blind spots in performance and testing of cord-connected SPDs – CPSC data

Figure 3 shows one example of the many cord-connected SPDs that failed in the field and were then submitted to the Consumer Product Safety Commission (CPSC) for evaluation. The photograph shows the back of the enclosure of a seven-year old SPD (pre-Second Edition UL 1449) which was reported as having occurred upon recovery from a power system outage – a classic scenario of temporary overvoltage occurrences.

Thus, real-world situations can occur in the field where some UL-listed SPDs might still be failing in an unacceptable manner when exposed to TOVs for which the actual available fault current might not have been included in the present mandated test regimen.

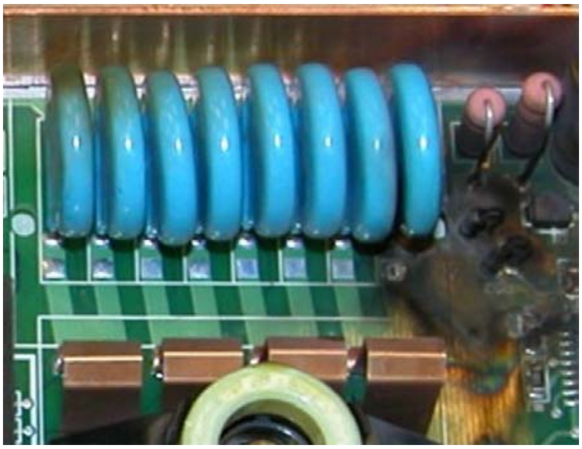
Figure 3 – Field failure submitted for assessment
(Courtesy U.S. Consumer Product Safety Commission)

Ongoing laboratory tests at the CPSC indicate that commercially available, UL-listed SPDs can experience unacceptable failure modes for TOV-induced failure in ranges not included in the present UL 1449 requirements for the available fault current. This situation indicates that there are some blind spots left in the available fault current range of the present test regimen prescribed by UL 1449, Second Edition.

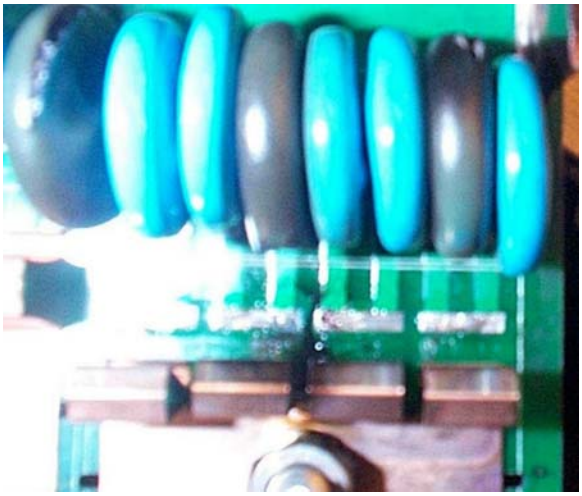
4.2 Blind spots in performance and testing of hard-wired SPDs – CH data

A combination of the Cutler-Hammer (CH) data on field failure returns and laboratory tests provides some further insights in the problems of black-box testing SPDs under an arbitrarily set range of available fault currents.

Figure 4a shows an example of in-field failure. In that example, there was no practical after-the-fact possibility of performing measurements of available fault current at that particular site, but a comparison with the results of hundreds of in-house laboratory tests led to the conclusion that the available fault current at this site must have been in a range of 5 A to 500 A because laboratory test samples tested outside this range (below 5 A fault currents and above 500 A fault currents) have totally different level and type of damage. To simulate in-field conditions in the laboratory and obtain similar results, the operator had to provide a power supply with an available fault current of 100 A. This shows that the range for this test procedure, which did replicate the in-field conditions, is not covered in any of present UL 1449 standards tests.



(a)



(b)
Figure 4
(Courtesy Cutler-Hammer)

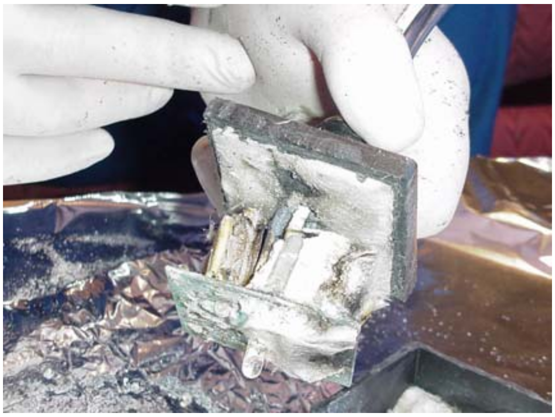
Figure 4b shows an example of an SPD failed at a 5 A fault current. Comparing the two figures (4a and 4b) does show the differences between a failure mode test with 5 A available fault current – the presently prescribed UL 1449 test – and a failure mode test performed with 100 A available fault. This example adds further strength to the point that some medium available fault currents must be included in SPD test requirements.

4.4 Blind spots in performance testing of hard-wired SPDs – Schneider Electric data

Figure 5a shows the results of a laboratory test performed on a new product under development to simulate an abnormal overvoltage test with an available short circuit current of 500 A. These hard-wired SPDs under test were designed and intended to be installed on the side of enclosures used with 120/240 Vac service entrance load centers. The value of 500 A was intended to replicate conditions when the SPD would be employed in remote locations where the available fault current from the local electric service provider is limited by the impedance of the long distribution circuits. This SPD might also be employed in locations where there would not be any secondary overcurrent protective devices. The only local overcurrent protective device might then likely to be the fused cutout on the primary of the local distribution class transformer. The use of a 500 A value represents an available fault current that is not presently specified as a standard test in any edition of UL 1449.

Figure 5b shows an example of one of several in-field failures in remote areas of the same rural coastal county. The available fault currents at these locations were greater than 100 A but less than 1000 A. This specific SPD was protected by 15 A fuses. The 15 A fuses were found intact and functional. However, the phenolic cover of the SPD had been overheated and was deformed. It was suspected that exposure to TOV conditions were major contributing factors in the in-field failures. The factory designs and construction of that specific model SPD was UL witness-tested to the Second Edition of UL 1449. and all the UL tests had been passed satisfactorily.

(a)



(b)
Figure 5
(Courtesy Schneider Electric)

5. WHERE IS THE DISCONNECTOR ?

The critical function of an SPD disconnector has not yet been sufficiently recognized although – with some hindsight – it should have been obvious. The seminal 1976 publication on metal-oxide varistors (“GE-MOV”) applications (GE Transient Manual [7]) includes several pages discussing the need and details of “fusing protection” and yet some present standards (IEC 61643 series [8]; [9]) do not mandate the application of a disconnector (optional as internal or external) while others (IEEE Std C62.34™-1996 [11]) do not provide any guidance on testing the disconnector function.

It is now urgent that this ambiguity on disconnectors be replaced by appropriate guidance or, better, clear mandates in SPD application standards.

Furthermore, the parameters cited for Class I test leave some ambiguity on the issue of what waveform is appropriate for applying the specified charge transfer, Q, to the test specimen. Emphasis given on charge transfer being the critical parameter can lead to performing the test with relatively short waveforms, which results in peak impulse current values in hundreds of kiloamperes. While such peak values do provide the stipulated values for the charge transfer, Q, they should be carefully reviewed for consistency with reality.

The high values of di/dt associated with a high peak of a short waveform would result in a large voltage drop in a cable postulated to bring the real-world surge to the targeted SPD. That means that the driving voltage at the “sending end” of that surge would be so high that a flashover of clearances would occur at that sending end, throttling further application of the surge current to the SPD at the receiving end (Martzloff, 1997, [12]). Thus, one must conclude that in the real world, SPDs will not be exposed to that type of high peak, short stress, although it may be a valid approach to demonstrate the capability of the SPD component for that charge transfer ($\int idt$), but only that.

Notwithstanding this somewhat reserved acquiescence to accepting the simple Q parameter as the significant one, a paper by Bartkowiak et al.[13] shows that the relationship between charge transfer and withstand capability is not that simple. Different stresses – and therefore different failure modes – in the case of distribution arresters are described in that paper, such as edge flashover related to the rate of rise di/dt, mechanical stresses related to i^2 and thermal effects in the zinc oxide grains that are related to an adiabatic or non-adiabatic heat deposition, depending on surge duration and ratio of the boundary-layer-to-grain volumes, as well as uneven current density related to the "skin effect" that increases the current carried near the periphery of the discs. I am not aware of a similar study having been performed on the typical 20 mm discs used in low-voltage SPDs. These smaller discs might not be as sensitive to the rate of energy deposition as the larger disks used in distribution arresters.

If now the SPD is associated with a disconnector (a feature that needs a clear mandate in SPD application standards) the fusible element of the disconnector responds to $\int i^2dt$, not $\int idt$. By applying an "equivalent" high peak (with a linear relation to the duration of the waveform) aimed at obtaining the stipulated Q, the disconnector is exposed to the thermal effect of the current, with a square-law relation to the duration of the waveform. Under these conditions, the disconnector is likely to open and thus provoke a judgment that the specimen SPD has failed the test. Worse yet, if the disconnector opens during the "equivalent" surge, the behavior of the package becomes unpredictable.

A more insidious consequence of demanding that the disconnector not open during the charge transfer test might be that the designers, anxious to met that criterion, might erroneously provide a disconnector with a time-current characteristic that would leave a blind spot in the functionality of the disconnector in the range of medium fault currents, as demonstrated by the examples provided in this paper.

One solution, perhaps the only one, is to by-pass the disconnector when performing the charge transfer test, but that might be seen as opening the black box and therefore be deemed unacceptable – one more reason why SPD standards should avoid the well-meaning but misleading black-box test philosophy and procedure.

6. CONCLUSIONS

The present situation in the guidance – or unclear mandates – for application of surge-protective devices is leaving gaps – blind spots – in test procedures and qualification tests that cry for redemption, as illustrated by the five examples cited in this paper. Greater cooperation, coordination, and candid consultations among standards-developing organizations, manufacturers, and end-users is one approach that would bring positive results. While some progress has been made in that direction, the present situation still leaves several gaps that urgently call for action, as listed below:

6.1. The present situation

- Lingering perception that "black-box testing" is the desirable and "fair" test method.
- Discrepancies between field failures and lab-induced failures observed under standard specifications.
- Lack of consensus on what is a reasonable number of tests in ferreting out blind spots.
- Insufficient knowledge of the range and values of real-world TOV scenarios.
- Insufficient recognition of the function and location of SPD disconnector

6.1. Recommended action items

- In a few words, but with much work implied, address all the concerns listed above !

7. ACKNOWLEDGEMENTS

The contributions of anecdotal but real-world data by the four organizations identified with the photographs and narratives (EPRI PEAC, US Consumer Product Safety Commission, Eaton/ Cutler-Hammer, and Schneider Electric) provided for me and – more important, for readers of this paper – valuable support for the "How not to test SPDs" theme, and all are gratefully acknowledged.

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