

TOV Effects on Surge-Protective Devices

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Reprinted from *Conference Record, Power Quality Exhibition and Conference*, Baltimore, October 25-27

Significance

Part 7 – Mitigation techniques

Among the diverse equipment permanently installed or plug-connected in low-voltage power distribution systems, SPDs have a special position because of the expectation that they perform an effective protective function against surges. However, because of the common misuse of the word “surge,” some expectations linger that an SPD might also protect equipment against temporary overvoltages (TOVs). The reality is that because of their intended deliberate response to any overvoltage, SPDs are perhaps more likely to be victims rather than protectors in a TOV scenario. This paper reports TOV susceptibility tests on SPDs, which can provide motivation for standards-developing groups toward careful assessment of SPD TOV sensitivity.

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INTRODUCTION

Motivation

Among the diverse equipment permanently installed or plug-connected in low-voltage power distribution systems, SPDs have a special position because of the expectation that they perform an effective protective function against surges. However (and unfortunately), because of the common misuse of the word “surge,” in spite of a specific IEEE definition [1] some expectations linger that an SPD might also protect equipment against temporary overvoltages (TOVs). The reality is that because of their intended deliberate response to any overvoltage, SPDs (if not properly designed or correctly used) are perhaps more likely to be victims rather than protectors in a TOV scenario. This paper reports TOV susceptibility tests on SPDs, which can provide motivation for standards-developing groups toward careful assessment of SPD TOV sensitivity.

Test program

Stresses to be applied to the SPD were defined on the basis of published reviews describing TOVs likely to be encountered in low-voltage power systems (ANSI C84.1, 1995 [2]; EPRI, 1996 [3]; Short, 2004 [4]). It must be emphasized that the prime objective of the tests was simply to obtain a description of the behavior of SPDs exposed to real-world TOV occurrences, not to perform exhaustive tests to assess the acceptability of failure modes, and even less safety issues. Table 1 shows the TOV stress levels selected from the review of TOV occurrences. The tests and post-mortem examinations, funded by EPRI sponsors, were performed by the laboratory staff of EPRI Solutions in Knoxville, TN (Nastasi, 2005 [5]).

Table 1 – TOV Stress levels selected for the test program

Test Stress Level	Imitated Condition	Magnitude	Duration
1	Poor voltage regulation	1.15 PU (138 V)	6 hours
2	During a fault	1.3 PU (156 V)	2 seconds
3	Loss of a secondary neutral	1.5 PU (180 V)	4 hours
4	Ferroresonance	2.0 PU (240 V)	1 minute
5	Commingling (contact to HV circuits)	3.0 PU (360 V)	1 second

There is growing recognition among standards-developing groups that a clear distinction must be made when assessing the results of an SPD stress test: It is permissible to have a device fail, as long as the failure mode is “acceptable” according to some agreed-upon criteria. The difficulty in the industry at this point is to agree on what can be called acceptable in the face of well-documented anecdotes of clearly unacceptable failure modes for some UL-listed SPDs that passed the present standardized tests (UL 1449, 1996 [6]). While rare, in-field failures of SPDs do occur, for a variety of causes. Manufacturers of SPDs become aware of these occurrences from returns that most manufacturers include as part of their warranty programs, allowing for some cases to be examined for determination of the cause of failure. The following Rogue’s Gallery presents a list (not limiting) of possible causes of SPD failures. As indicated in the second category of that list, some of these are not related to the occurrence of a TOV and thus will not be addressed in this paper.

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A ROGUE'S GALLERY OF CAUSES FOR SPD FAILURES

Category 1 – TOV related failures

Response to system overvoltages

- Insufficient TOV withstand capability of the SPD
- Utility problem (e.g. fuses opened on transformer primary side during a fault of upstream equipment)
- Commingling of power lines (conductors of higher voltage falling on conductors of lower voltage)
- Voltage oscillations when local load is larger than local power generation capability
- Switching on and off capacitor banks
- Unregulated voltage or poor voltage regulation
- Conductor isolation breakdown
- Generator overspeed or overexcitement

Interactions with adjacent electrical equipment

- Electrical arc furnace
- Sudden failure on nearby large loads
- Voltage notches caused by rectifiers
- Voltage oscillation due to switching on and off large loads or sudden loss of load
- Voltage oscillation due to ferro-resonance
- High frequency harmonics from various sources
- Reflection waves caused by variable-frequency drives
- Arcing on circuit breakers during opening and closing
- Unbalanced current flow in multi-phase systems
- Uncoordinated alternate or secondary power source on site
- Non-synchronized coupling of local generator with utility power grid

Category 2 – Not-TOV related failures

Incorrect installation practices

- Miss-wiring (SPD or other equipment surrounding SPD) during installation
- Misapplication (e.g. SPD designed for 208 Vac system was connected to the 480 Vac)
- Elevated ambient temperature from external sources (not caused by SPD)
- Neutral conductor connected to SPD was lost after installation
- High potential test applied to evaluate dielectric strength of isolation

Mis-wiring of power grid

- Poor power quality on construction sites with unfinished power grid
- Bad or non-existing neutral connection somewhere else in the grid
- Bad connection between phase conductors connected in series
- Poor grounding connection

Imposed surge currents

- Lightning surge on secondary system
- Direct flash to the building

Inherent SPD problems

- SPD (MOVs, SAD, gas-tube) components aging
- SPD auxiliary (monitoring) components breaking down

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TEST PROCEDURES

Selection of specimens

The SPD test specimens were obtained on the basis of being readily available from local vendors, typical cord-connected types used for point-of-use protection of appliances (three varieties), and permanently connected intended for installation at service entrances (two varieties). This selection was arbitrary, emulating the choice that an end-user (for a cord connected SPD) might make when browsing the shelves in a store, or the choice that an electrician might make at the warehouse for a permanently connected SPD. Price was not a consideration. To avoid identification of specific brands – not the objective of the project – only a generic description of the specimen SPDs is provided in this paper. Tables 2 and 3 show the features that are listed on the respective SPD packages. In addition to the SPD under test, a 60-W incandescent lamp was connected as a “pilot” in parallel with the specimen SPD to give the test operator a visible indication of what a dweller would see in a residential environment. In cases of moderate TOVs lasting for several hours (quasi-oxymoron notwithstanding), such a visible indication could provide to the occupant a warning, if noticed, of an abnormal condition, giving a chance to turn off sensitive equipment before damage might occur.

Cord-connected SPD specimens

Three specimens were included in the program, identified as SPD1, SPD2, and SPD3. The first two SPDs were of the power-strip (bar) type, typical of what consumers can find in electronic and electrical supply stores. The third type, slightly more sophisticated, was a box-type, still a consumer-oriented product.

Cord-connected SPDs generally have thermal fuses to aid toward an acceptable failure mode (no fire hazard). These fuses are not replaceable, so the SPD must be discarded (if that situation is made clear to the user, because some designs can leave the output energized after opening of the fuse (see Martzloff, 1998 [7*])¹, a situation that was noted for some of specimens in this project. However, at least one brand is available on the market, but could not be included in this project, which has a resettable disconnect circuit. That feature protects the SPD itself AND the load from a TOV, by opening the resettable circuit. Such a load interruption might be unnecessary for a benign TOV, but is likely to be preferred by users who desire the extra protection and will gladly accept to reboot their computer rather than risk having it fried by a TOV.

Permanently wired SPD specimens

The two specimens obtained for this project are of the type for which a permanent connection requires installation by a qualified electrician. They are of the type classified as “one port” by SPD standards, meaning that they are connected in shunt at some point of the installation, and do not carry the load current, in contrast to the cord-connected SPDs that have an input port (the cord) and an output port (receptacles) with or without some series impedance between the two ports. Any disconnect included in these permanently wired SPDs, by design, will not interrupt power supply to the installation, but merely separate the failed SPD from the installation.

¹ Bibliography citations for reference numbers with an asterisk [N*] can be accessed on line via a hyperlink shown in the bibliography listing.

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Table 2 – Features of cord-connected SPD1, SPD2, and SPD3

Specimen ID	Technology	Nominal MOV Voltage	Manufacturer claims
SPD1	130-V MOVs	195 V	10 kA 490 joules \$25,000 protected equipment guarantee Building wiring fault indicator Catastrophic event protection Fail Safe Mode IEEE let-through rating and UL 1449 compliance Noise filtering Protection working indicator Status indicator LEDs TVSS ratings 330 V (L-N) (L-G) (N-G)
SPD2	130-V MOVs	201 V	750 joules \$25,000 connected equipment warranty TVSS 330 V (L-N) (L-G) (N-G)
SPD3	multiple MOV paths + inductors and capacitors	231 V 218 V	140 V RMS clamping 2200 joules/85,000 amps \$50,000 ultimate lifetime insurance UL1449 listed - surge suppression (330V let-through), UL1283 listed - EMI protection, UL1363 listed – power tap, CUL approved to CSA Transient suppression voltage 330 V (L-N) (L-G) (N-G)

Table 3 – Features of permanently connected SPD4 and SPD5

Specimen ID	Technology	Nominal MOV Voltage	Manufacturer claims
SPD4	Multiple MOV + multiple gas discharge + sine-wave tracking	176 V	Multiple MOVs with built-in thermal fuses Gas discharge tubes in series with MOVs 100-kA 8/20- μ s protection (50 kA per mode) Transient discriminating technology for long service life Ideal for sites with poor voltage regulation Thermal protection Over-current fusing UL 1449 Edition 2 listed All modes protected Dual LED status indication EMI/RFI sine-wave tracking filter
SPD5	Multiple MOV + multiple gas discharge	206 V	Multiple parallel MOVs Gas discharge tubes in series with MOVs Thermal fusing Catastrophic surge circuit Single-pulse energy dissipation 2700 joules Spike capacity 60 kA (each wire) Line voltage 120/240 1 phase 50/60 Hz Clamping level (TVSS voltage) 400 V Initial clamping level 240 V

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Note that association of MOVs and fuses simply means that the thermal cutout is physically located on the circuit board so that it has intimate contact with the associated MOV(s). The heat generated by the overstressed MOV then triggers the heat-responsive cutout to open the circuit before a massive failure of the MOV can occur. The method of creating intimate contact between the MOVs and the cutout varies from manufacturer to manufacturer. Some rely only on proximity of the two components. Others wrap a piece of tape around the MOV and the cutout to help ensure that they are held in contact. At least one MOV disc manufacturer is now offering MOV discs which include a series-connected thermal cutout maintained in intimate contact with the disc by applying the usual coating after the cutout has been added.

TEST RESULTS

The “Crispy Factor”

Post mortem examination of the test specimens included measurements of the characteristics of the SPD components as well as a visual inspection for which a short-hand description was created here. While it is doubtful that these terms will become official IEEE or IEC definitions, they will suffice for the purpose of tersely describing the condition of the MOV in the tabulations of this paper, Figures 1 through 4 show the extent of MOV damage from extreme to benign.



Figure 1
Crispy Factor CF3, indicating obliteration



Figure 2
Crispy Factor CF2, indicating a flaky surface and some loss of physical structure



Figure 3
Crispy Factor CF1, indicating a single split or hole



Figure 4
Crispy Factor CF0, indicating an intact MOV covered with soot from other MOVs

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Results for cord-connected SPDs

Details of the postmortem analysis of the cord connected SPDs are given in Table 4. The test stress levels 1 (138 V – 8 hours) and 2 (156 V – 2 seconds) did not produce any failure so the table does not include these tests. Crispy factor (CF) levels for each of the MOV modes (L-N, L-G, N-G), and fuse (F1, F2) status are shown. Also note whether the load will be left energized or not after failure of the SPD components.

Table 4 – Results and Postmortems on Cord-Connected SPD1, SPD2, and SPD3

Type and Technology		Test Stress 3	Test Stress 4	Test Stress 5
		180 V – 4 Hours	240 V – 1 Minute	360 V – 1 Second
SPD 1 Cord-connected strip	130-V MOV	Fail Load off L-N MOV- CF1, open L-G MOV- CF3, open N-G MOV – CF2, short F1 = open F2 = open	Fail Load still on* L-N MOV CF0, intact L-G MOV CF1, short N-G MOV CF0, intact F1 = intact F2 = open	Fail Load still on* L-N MOV – CF0, intact L-G MOV – CF1, open N-G MOV – CF0, intact F1= intact F2 = open
SPD 2 Cord-connected strip	130-V MOV	Fail Load still on* L-N MOV – CF0, OK L-G MOV – CF3, open N-G MOV- CF3, open F1 = intact F2 = open	Fail Load still on* L-N MOV- CF0, OK L-G MOV- CF2, short N-G MOV- CF2, short F1 = intact F2 = open	Fail Load still on* L-N MOV- CF1, short L-G MOV- CF3, open N-G MOV- CF2, open F1 = intact F2 = open
SPD3 Cord-connected box	multiple MOVs + filtering	Fail Load off L-N MOV7 CF2, short All other MOV- CF0, OK F1 = open F2 = intact	Fail Load off L-N MOV7 CF3, open All other MOV- CF0, OK F1 = open F2 = intact	Fail Load off L-N MOV7 CF3, open L-G MOV5, CF1, short All other MOV- CF0, OK F1 = open F2 = open

Results for permanently-connected SPDs

Details of the postmortem analysis of the permanently-connected SPDs are given in Table 5. Both SPD 4 and SPD 5 survived the “expected possible” occurrences of TOVs as defined by tests 1 through 4. The highly abnormal and rare Test stress 5 scenario of commingling, defined as 3.0 PU, that is, 360 V for a 120-V-rated device, did cause an acceptable internal failure of one of the multiple parallel paths of these SPDs. The significance of that performance is that the SPDs emerged with neither loss of their primary surge-protective function (albeit with a somewhat reduced capability) nor cut-off of the power to the connected loads. Maintaining power to the loads is an implicit requirement for a shunt-connected (“one port”) SPD.

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Table 5 – Results and Postmortems of Permanently Connected SPD4 and SPD5

Type	Technology	Test Stress 5
		360 V – 1 Second
SPD4 permanently connected	multiple MOV + multiple gas discharge + sine-wave tracking	Internal partial failure Acceptable One path with three MOVs + associated spark gap open Load still on (no provision to open the load, an intended design) Parallel MOV paths OK
SPD5 permanently connected	multiple MOV + multiple gas discharge	Internal partial failure Acceptable One MOV shorted, its fuse open Load still on (no provision to open the load, an intended design) Parallel MOV paths OK

DISCUSSION

Susceptibility to TOV

There are two aspects to consider while defining SPD specifications related to TOV susceptibility. One is the Maximum Continuous Operating Voltage (MCOV) of the SPD, the second one is the SPD disconnecter response time under fault conditions.

MCOV issues

The MCOV is a parameter that is declared by the SPD manufacturer on the basis of in-house information on what the SPD can accept with long-term stability and without degradation. For the last 30 years, industry has focused on offering low clamping voltages, motivated by commendable goals of providing surge protection for loads that were assumed to be vulnerable to surges occurring on their power supply input. This perception led to selecting MOV disc thicknesses that produced relatively low measured limiting voltages for packaged SPDs, perhaps without realizing that such a selection made them unduly susceptible to TOVs (Martzloff & Leedy, 1989 [8]). Actually, tests performed by independent researchers (Anderson & Bowes, 1990 [9]; Smith & Standler, 1992 [10]) have shown that typical appliances are robust enough to withstand moderate surges and the clamping voltages of well-matched SPDs, thus do not require the low clamping level of 330 V for 120 V applications unwittingly encouraged by the first 1985 edition of UL Std 1449. Of course, more severe surges require protection afforded by SPDs.

Reports and papers have been published with the conclusion that the actual suppressed voltage at the load terminals can be higher than the clamping voltage of the SPD if the distance between the SPD and the load equipment is significant IEC 62066 2002 [11]; Jinliang et al., 2005 [12]). This means that when a required clamping voltage protection level is specified for load equipment, there should always be a margin between the clamping voltage of SPD and the specified protection level at the load terminals.

Although, this misperception of “lower is better” is now being debated, there is unfortunately no consensus among SPD experts on what level of MCOV of SPD would be considered a “safe level”.

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As a practical matter, commercial MOV discs are produced with a tolerance window on their measured limiting voltage, which is directly related to their physical characteristics (thickness and ceramic structure). Packaged SPD manufacturers then assemble their SPD packages by using discs that can be sorted for a match – a parallel operation goal – as well as for the MCOV which their design goals have defined. To repeat the description given above for the MCOV rating of an SPD, it is a manufacturer’s rating, which cannot be “verified” by test, it is a declared value that reflects the manufacturer in-house and in-field experience.

In the last few years during meeting of SPD experts, consensus among SPD manufacturers, SPD users, and general interest contributors has been somewhat elusive. There were different proposals for what the MCOV of the SPDs should be: 1.15 PU; 1.20 PU; 1.25 PU; 1.375 PU; 1.73 PU, all attempting to provide the desirable goal of low clamping voltage without falling into the trap of undesirable risk of TOV-induced failures. Indeed, a quick Internet survey of the MCOV offered by SPD manufacturers yields a range of 1.1 PU to 1.25 PU, with some of them indicating a higher value, in particular for hybrid designs. In this situation, it might be reasonable to accept at least a “middle way” value 1.25 PU as Solomon’s solution although an incremental raising of the MCOV would decrease TOV sensitivity.

The decision about MCOV becomes more complicated in real life, when multiple clamping components inside SPD have to be considered. In order to increase surge current capability the SPD manufacturers design multiple clamping components that are connected in parallel. See the companion paper “*Clearing the L-N-G and IEC TN-C-S alphabet soup for SPD protection modes*” in the proceedings of this Conference for a discussion of using parallel multiple clamping components.

SPD disconnecter response time

Once the weakest clamping component inside SPD fails, the high fault current will flow through the SPD, causing the fault energy to be deposited inside SPD in a short period of time. Now, the SPD disconnecter has to play to role of controlling how much fault current energy will be deposited into the shorted SPD. If the SPD disconnecter is correctly sized, the fault will be contained. The SPD can then be replaced and no additional damage will be observed. Unfortunately, an SPD disconnecter is not a mandatory part of the SPD design according to the present UL Std 1449 [6].

Hindsight on MCOV ratings

TOV-induced failures of low-voltage SPDs are in part the result of SPD TOV withstand levels that do not match the actual TOV environment of low-voltage power distribution systems. In contrast, for the high-voltage environment, the well-accepted utility-oriented philosophy of Basic Insulation Level (see Fisher & Martzloff, 1976 [13*]) produced caution in the design of arresters (Sakshaug et al., 1977 [14*]) with adequate TOV withstand levels. With hindsight, the initial enthusiasm for an answer to the quest for an effective and economical transient suppressor in consumer products (Harnden et al., 1972 [15*]), is probably at the source of the unfortunate selection of low measured limiting voltage levels – and consequently the related MCOV rating – of MOV discs with a now questionable perception of “lower is better” for surge protection (Martzloff & Leedy, 1989 [8]) when TOV sensitivity issues arise.

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SUMMARY AND CONCLUSIONS

Typical commercial surge-protective devices are indeed susceptible to temporary overvoltages that are likely to occur on low-voltage power systems. Their responses vary from no damage to complete destruction. For the five stress levels selected in the project and the inherent clamping levels built-in by the diverse manufacturers of the test specimens, their diverse responses were observed as shown in Table 6. The “pilot” 60-W incandescent lamp survived the first three stress levels, in particular four hours at Test Stress Level 3 (4 hours at 1.5 PU – visibly brighter), a condition that might then be signaled to the occupant, if noticed, in time to take corrective action such as turning off appliances and contacting the energy service provider.

The three specimens of cord-connected SPDs survived the two lower stress levels but could not survive the scenario of a lost secondary neutral, which although infrequent, has been documented in many instances. Some of these specimens maintained the load outlet energized but with no protection against surges, a condition that most end-users would probably not welcome if they were informed of that situation by adequate status indicators (assuming that the end-user would regularly monitor these indicators (Martzloff, 1998 [7*]). If only the clamping level of the MOVs in these packages were slightly higher, they would be able to survive the loss of neutral scenario, and still provide adequate surge protection for reasonably robust loads.

Table 6 – Summary results

Stress Level	Imitated Condition	Magnitude	Duration	Effect on SPD	
				Permanently connected	Cord connected
1	Poor voltage regulation	1.15 PU (138 V)	6 hours	No damage	No damage
2	During a fault	1.3 PU (156 V)	2 seconds	No damage	No damage
3	Loss of secondary neutral	1.5 PU (180 V)	4 hours	No damage	All fail Some with load left on Some with load disconnected
4	Ferroresonance	2.0 PU (240 V)	1 minute	No damage	
5	Commingling – High voltage onto secondary system	3.0 PU (360 V)	1 second	Partial failure but still functional with acceptable loss of capacity	

The two specimens of permanently connected SPDs were robust enough to survive four of the emulated TOV scenarios, and even for the rare case of commingling (assuming that it would not last more than one second because the breaker of the invading high voltage system can be expected to clear the fault) these two specimens were not destroyed. A more severe scenario of commingling – an unpredictable event from the point of view of SPD users – might still fail these SPDs.

As stated in the introduction, safety considerations were specifically excluded from the scope of this project. Nevertheless, in an actual installation, they must be considered. A lower MCOV can cause a higher TOV-induced SPD failure rate in the field, and a longer response time of the disconnecter causes more severe failure of the SPD. This means that from a safety perspective, the SPD should be specified with higher MCOV and faster SPD disconnecter.

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Thus, an “acceptable” response of the SPD depends on selecting an appropriate MCOV level as well as an effective disconnecter design. The authors are hoping that new TOV testing might be conducted in the near future by some independent laboratories. Other important parameters, not addressed in this paper, should be tested and documented, such as short-circuit current rating with specific power system parameters, effect of available fault current levels on specific energy, total energy deposited. Based on those parameters, valuable lessons could be learned about relevant SPD characteristics. Hopefully, current discussions in standards-developing groups will address these parameters, and this paper might help focusing attention on the need.

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² A useful resource of further bibliography references is the public-domain SPD Anthology, from which the hyperlinks shown in the citations have been extracted. This Anthology includes an Annotated Bibliography of over 200 papers by many researchers (those published before 2001) and Martzloff papers (published 1963-2004) relevant to surge protection in low-voltage AC power circuits; it can be accessed at: <http://www.eeel.nist.gov/817/817g/spd-anthology/>