Lingering Lead Length Legacies in Surge-Protective Devices Applications

François Martzloff
National Institute of Standards and Technology

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Significance

Part 5 – Monitoring instruments, laboratory measurements and test methods
Part 6 – Textbooks and tutorial reviews

Two experiments are reported to show how some lingering inherited misconceptions about the applications of surge-protective devices (SPDs) can lead to erroneous or cost-ineffective attempts to address the issue of lead length.

The first experiment demonstrates the fallacy of the “four-terminal SPD” configuration if taken at face value without additional precautions on lead dress.

The second experiment provides quantitative information on the actual effect of lead length. With this information, designers and installers can place the issue in a realistic perspective and avoid unnecessary effort.

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François D. Martzloff, *Life Fellow, IEEE,* and Kermit Phipps, *Member, IEEE*

***Abstract*—Two experiments are reported to show how some lingering inherited misconceptions about the applications of surge-protective devices (SPDs) can lead to erroneous or cost-ineffective attempts to address the issue of lead length. The first experiment demonstrates the fallacy of the "four-terminal SPD" configuration if taken at face value without additional precautions on lead dress. The second experiment provides quantitative information on the actual effect of lead length. With this information, designers and installers can place the issue in a realistic perspective and avoid unnecessary effort.**

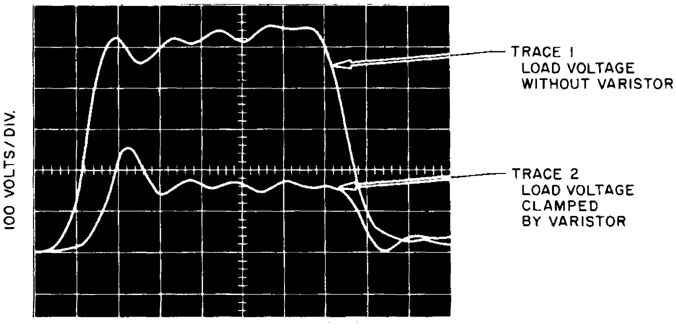
***Index Terms*—Electromagnetic coupling, length measurement, surge protection, testing, voltage measurements.**

I. Introduction

Many references found (inherited) in the literature imply that lead length is a significant factor to consider for correct installation and characterization of surge-protective devices (SPDs). This perception has led to the design of "four-terminal" one-port SPDs where the incoming power must be routed through the device terminals,[1] rather than using an SPD with simple shunt connection with a pair of leads of unspecified length connected at some point of the system. However, both perception and design miss the point that the problem is actually one of mutual inductance as well as "lead length." It is indeed important to recognize that to achieve an optimum surge protection, connecting leads of SPDs should be as short as possible. Yet not only long lead lengths, but also significant loop area formed by the connecting leads, will add an inductive voltage to the protective voltage of the SPDs, degrading their performance. The perception was further complicated by concerns about the "speed of response" issue. After a brief review of some old issues, this paper reports the results of two experiments aimed at placing the lead length issue in the proper perspective.

II. Historical Perspective

Concerns about the undesirable performance degradation of improperly installed surge-protective devices are not new. In the high-voltage arena, the concepts of "separation effects" and "connecting lead wires" have been recognized for more than a half-century (Witzke and Bliss, 1950 [1]); (IEEE Std. C62.2-1987[2] [2]), and the recent IEC 61 643-12 (2002) [3] is a comprehensive guide for low-voltage applications.[3] In the low-voltage arena, the situation has been complicated by misguided attention to the issue of "speed of response" and concerns about "overshoot" in the application of SPDs, fueled by debates about relative merits of emerging technologies such as metal-oxide varistors (MOVs) and silicon avalanche diodes (SADs). The debates on this issue were quite active soon after introduction of MOVs and SADs in the seventies. At that time, so many papers were published that any attempt to recite them entails a severe risk of offending the authors who might be overlooked in a list of references, so that we will not take that risk here. The debates have now abated although lingering perceptions or misperceptions remain.



Source: Fig. 3.18, GE Transient Voltage Suppression Manual [4]

Fig. 1. Response of MOV to nanosecond pulse [4].

For MOVs, a typical application manual published in the seventies [4] addressed both the issues of "speed of response" and "lead length" as illustrated by Figs. 1 and 2 (overleaf) excerpted from this manual. Other documents, such as IEEE Std. C62.33-1982 [5] attempted to place speed of response and overshoot in perspective and de-emphasize the issues, but were not entirely successful, to wit the claims for nanosecond response that still appear on the wrapping of some commercial SPD packages. Some justification for the emphasis on speed of response can be found in historical context, when interest was arising about ensuring protection against the nuclear electromagnetic pulse, and might still be valid for some military applications. In more mundane modern surge protection for today's industrial, commercial, and residential ac power circuits, the perspective is different. Reality checks and economic considerations suggest that these concerns might be an overkill

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F. Martzloff is with the National Institute of Standards and Technology, Gaithersburg, MD 20899-8113 USA (e-mail: f.martzloff@ieee.org).
K. Phipps is with EPRI PEAC Corp., Knoxville, TN 37932 USA.
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[1]This "four-terminal SPD" is a one-port, shunt SPD, which should not be confused with the two-port SPD. See definitions and notes in IEC 61 643-12 [3].

[2]In this historical perspective, unlike standards where the latest edition is explicitly specified, we quote the date of the original publication as available to us. In the case of C62.2, we speculate that the issue of separation effects might have appeared in earlier standards such as ANSI (not IEEE) C62.2-1981.

[3]However, this standard needs 123 pages of English text; we are attempting in this paper to ferret out only the items relevant to this lead length issue.

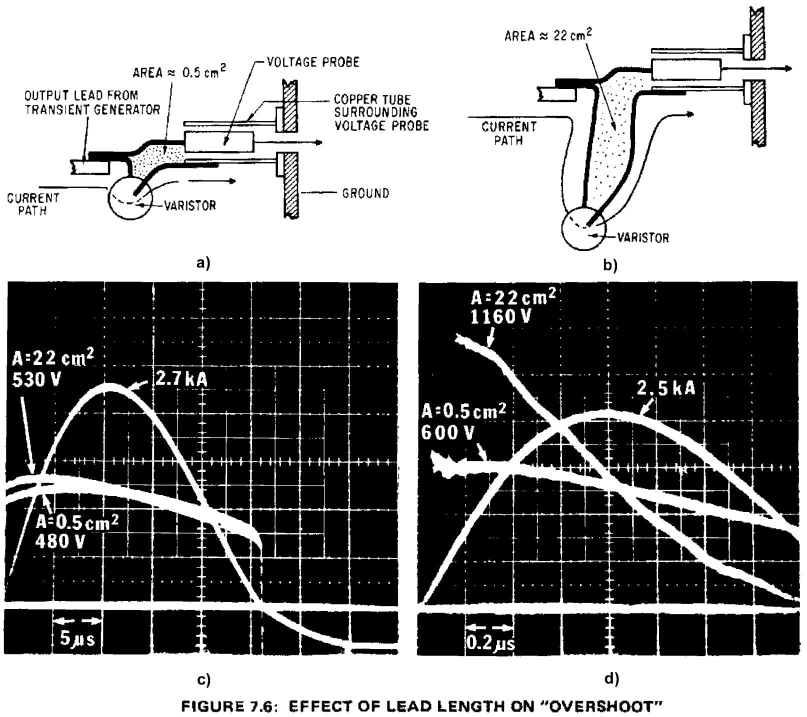

Fig. 2. 1978-vintage demonstration of lead length effect with fast-rising surges for two different "lead lengths" (a) Minimal loop area. (b) Excessive loop area. (c) Current rise of 8 μs. (d) Current rise of 0.5 μs.

in surge protection for circuits where the propagation of fast surges is limited [6] and typical wiring practices do not allow the sophistication of perfect connections in those applications.

Therefore, in this paper we will not go beyond a brief review of the old issues of speed of response and overshoot, but will concentrate on discussing the lead length that seems to be the lingering and misunderstood issue.

A. Speed of Response

For instance, Fig. 1 shows an oscillogram recorded to document the response to fast-rising pulses by an MOV disc inserted in the coaxial test fixture necessary to observe this submicrosecond pulse without test connection artifacts [7]. Indeed, the experiment confirmed the claim of fast speed of response of the intrinsic MOV material, but practical devices are generally not fitted in coaxial packages—just what the tutorial experiment reported later in this paper did require.

B. Overshoot

In Fig. 1, one might consider that the "TRACE 2" indeed display an overshoot that may be significant when concerned with nanosecond response of an MOV. However, for this context of surge mitigation in ac power circuits, very short picosecond pulses such as that shown in Fig. 1, or the EFT pulses defined in IEC 61 000-4-4 [8] and IEEE C62.41-1991 [9] have to travel only a few meters away from their origin to have their rise time and duration stretched into tens of nanoseconds or more [10].

Fig. 2 shows the test fixture arrangements and resulting performance for two current impulses with rise times, respectively, 8 μs and 0.5 μs [11]. These two rise times were not arbitrarily selected—our readers will readily recognize what became the IEEE Std. 587-1980 waveforms [12]. However, creating and injecting the 2.5-kA, 0.5-μs pulse into the test circuit required great care, to avoid spurious signals, illustrating again that such conditions rarely, if ever, do occur in real-world situations [13]. The original figure caption of the GE Transient Manual included in Fig. 2 mentions both lead length and overshoot, a regrettable mention—with hindsight—because it focuses attention on lead length, which is not the direct cause of that "overshoot."

The perceptive reader at that time might have noticed that the test fixture sketches in the figure correctly emphasized the issue of *loop area*, but the caption provided in the original 1978 figure is perhaps responsible for launching lead length legacies by focusing on *lead length*. Small wonder then, that so many lengthy debates and test specifications have been concerned with lead length rather than the direct effect of electromagnetic coupling between the two loops involved in an installation—the injected surge current loop and the protected equipment loop. Nevertheless, there is some redeeming tutorial value in that figure, which we will now briefly discuss.

C. Electromagnetic Coupling Between Loops

In Fig. 2, it should be noted that the traces were superimposed by multiple exposures and are not synchronous, so no attempt should be made to correlate exactly the timing of the voltage and current traces. Nevertheless, the inductive coupling mechanism is apparent in that the maximum voltage occurs at the beginning of the current pulse (maximum di/dt). Observe the large "overshoot" on the right-side oscillogram for the 22-cm^2 area loop and the more modest voltage for the 0.5-cm^2 area loop. As further evidence, the amount of "overshoot" for the two traces disappears at the point of current peak $(di/dt = 0)$; at that point, the voltage trace indicates the "true" level of the voltage limiting action of the MOV disc, free from spurious inductive effects.

In principle, the coupling aspect is simple, as illustrated in Fig. 3, which shows how the changing magnetic flux created by the flow of surge current in the circuit at left (Loop "A") induces a voltage in the circuit at right (Loop "B"). Thus, the load that

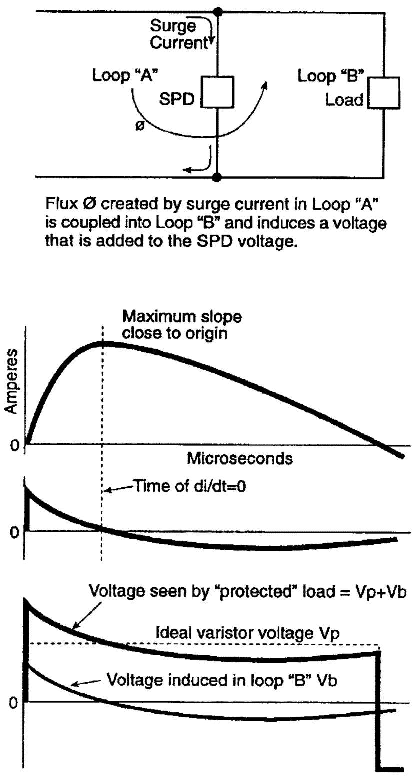

Fig. 3. Coupling of magnetic flux into the load loop.

was expected to be protected at the limiting level of the SPD actually sees that limiting voltage ***augmented by*** the induced voltage, as shown by the waveforms drawn in Fig. 3.

IEC 61 643-12 [3] also addresses this effect in Annex K. Figure K-6 of that annex, redrawn here as Fig. 4, is similar to our Fig. 3, but is relegated to a distant annex. In contrast, the Fig. 10 of the IEC document (redrawn here as Fig. 5), is found in the main body under the heading of "Influence of the connecting *lead length*" (italics ours) and, thus, appears to support the four-terminal approach by designating it as "preferred scheme"—but does not qualify it with a discussion of the possible electromagnetic coupling.

Note also that this connection arrangement still falls under the category of "one-port SPD" because there is no impedance between the "input" and "output" terminals, as would be the case for a "two-port SPD."[4] So, the idea of "lead length" as a prime and perhaps sole factor lingers on into the 21st century. This situation is what motivated us to conduct the experiments reported in this paper.

To quantify the effect of electromagnetic coupling between the two loops, we conducted a first experiment using a specially-constructed coaxial SPD to be inserted in a well-defined configuration of the two loops—the incoming surge loop "A" and load loop "B" as defined in the schematic circuit representation of Fig. 3.

[4]The IEC definitions read:
one-port SPD: SPD connected in shunt with the circuit to be protected. A one-port device may have separate input and output terminals without a specified series impedance between these terminals.
two-port SPD: SPD with two sets of terminals, input and output. A specific series impedance is inserted between these terminals.

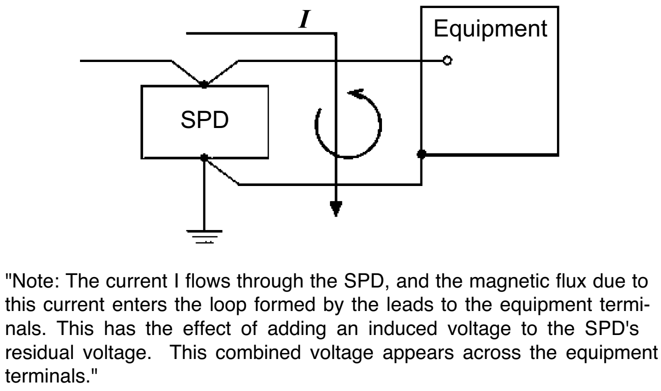

Fig. 4. Redrawn figure K.6 and note from IEC 61 643-12.

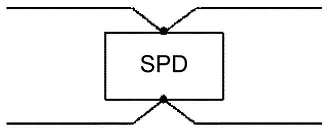

Fig. 5. Redrawn Fig. 10 "preferred scheme" from IEC 61 643-12.

III. New Experiments

The first experiment addresses the issue of the inductive coupling between adjacent loops, and the misleading perception that a four-terminal arrangement, such as that shown in Fig. 5, automatically circumvents the lead length issue.

The second experiment deals with the real issue of lead length for shunt-connected ("one port") SPDs, and provides some quantitative information on the magnitude of the effect as determined by surge current parameters and, indeed, lead length.

A. Coupling Between Adjacent Loops

For this demonstration, a "coaxial MOV" unit was constructed as shown on Fig. 6, allowing measurement of the "true" limiting voltage of the MOV without any significant inductive coupling. A 40-mm-diameter MOV disc was drilled at its center to allow connecting the core conductor of a coaxial cable to the top electrode, with the shield of the cable connected to the bottom electrode. Fig. 6 is a cross-section view of the device, which has complete rotational symmetry. A cap (cross hatch) is soldered to the top electrode and a sleeve (cross hatch) is soldered to the bottom electrode. Connections could be made at any point of the cap and of the sleeve; for the purpose of showing the device in a cross-section, terminal connections are represented on the left and on the right, but are at the same potential. According to the principle of the "four-terminal SPD," the incoming power supply (presumed to include a surge) would be connected at the left of the device, and surge-free (or at least mitigated) power for the protected load would be available at the right of the device. The "true" MOV voltage resulting from a surge can then be observed at the end of the coaxial cable. This structure was only aimed at the demonstration, not as a practical low-voltage SPD, but was inspired by old discussions on how to make a distribution arrester consisting of three parallel-connected stacks of MOV discs arranged at 120° with the power take-off at the center of the triangle [14].

Using this special coaxial MOV, measurements were performed on several simplified configurations of lead geometry, including the so-called "four-terminal SPD" suggested by

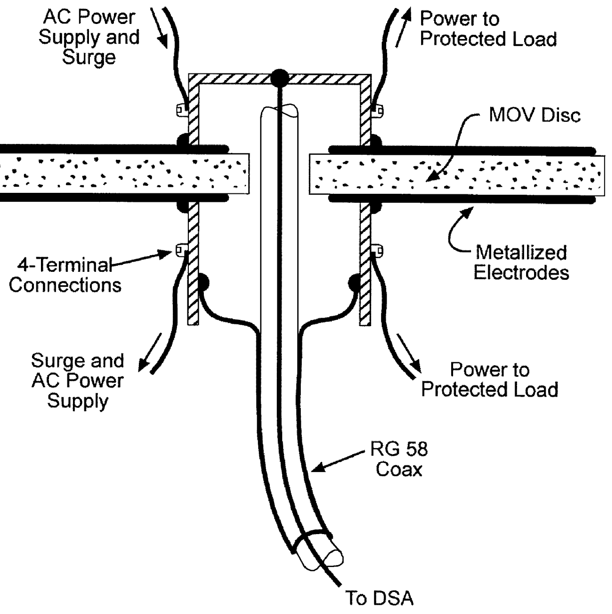

Fig. 6. Coaxial arrangement of test MOV.

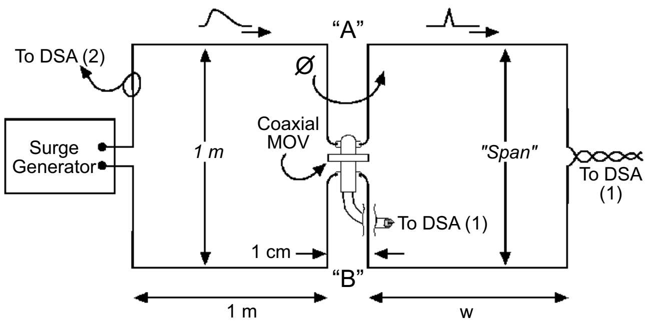

Fig. 7. Test circuit for quantifying inductive coupling.

some authors and offered in some commercial packages. Fig. 7 shows the test circuit and definition of the terms "span" and "w" (width). The test circuit consists of two well-defined rectangular loops of conductors with the dimensions shown, mounted on a common sheet of insulating material. On the left, a loop in which the applied surge current is driven into the coaxial MOV; on the right, a loop representing the path of the power supply toward the protected load—in this case, the voltage input of a digital signal analyzer (DSA). The surge current imposed on the MOV (maintained at the same level for all the tests by keeping the same setting on the surge generator) is monitored by a current-viewing transducer and fed to a second channel of the DSA. Bonding the conductors of the two loops at "A" and "B" allows obtaining a configuration equivalent to that of a conventional two-terminal, one-port, shunt-connected SPD.

Figs. 8 and 9 (overleaf) show the results obtained with two different standard surge waveforms—the Ring Wave and the Combination Wave of C62.41-1991 [9] for fixed dimensions (1 m) of the surge loop (left square in Fig. 7), and a constant width ($\mathrm{w} = 1\ \mathrm{m}$) but decreasing span of the measurement loop (right square in Fig. 7). Maximum decrease of the span would of course be accomplished by twisting the leads that go to the DSA, immediately from the point of attachment to the MOV. And the ultimate minimum span is the coaxial cable output from the MOV.

The oscillograms of Fig. 8 (for the relatively high di/dt of a Ring Wave) show, from left to right, how the inductive voltage can be reduced by decreasing the "span" of the loop that feeds power (and the mitigated surge) to the load. For the first of the oscillograms (at left), the two loops have a portion of the circuit in common by bonding the two corners of the squares above ("A") and below ("B") the MOV, clearly the worst possible case, with a relatively large span representing a very poor lead arrangement.

The next oscillogram toward the right shows the case of the "improved" four-terminal SPD configuration: the resulting protective voltage is only reduced from 624 to 618 V (the three-digit values being read from the numerical display of the DSA, not from the oscillograms). That is hardly an improvement, and it is perhaps below the variability of the repeated surges and digitizing noise.[5] This negligible difference between the two configurations demonstrates the fallacy of the four-terminal configuration if not accompanied by attention to the lead dress and resultant electromagnetic coupling, as can be seen in the oscillograms following these first two. Going on toward the right, the span is progressively decreased with corresponding decrease (improvement) of the protective voltage, until the ultimate (but impractical in the field) idealized configuration of the coaxial MOV with voltage read from the coaxial cable connection (zero span and zero loop width, $\mathrm{w} = 0$).

The oscillograms of Fig. 9 show, for a Combination Wave, and from left to right, the worst case of a large inductive coupling (made equivalent to the common lead configuration by bonding the corners "A" and "B" of the square loops), the four-terminal coaxial MOV arrangement with a span of 1 m, and the measurement taken at the output of the coaxial cable.

With that gentler rate of rise (a fifth of that of the Ring Wave for the current levels injected in this experiment), the effect of inductive coupling is negligible. (The waveforms are quite similar, only the DSA-generated peak values overwritten in the oscillograms show a difference). Of course, if the amplitude of the surge current were higher, the effect of the inductive coupling would be higher. Because this inductive effect is linear, in comparison with the nonlinear voltage-limiting response of the MOV, it will become increasingly noticeable for higher surge currents. However, there is a limit to the di/dt rate of change that can be imposed at the sending end of a branch circuit, because the voltage necessary at the sending end for driving such a steep current toward an SPD at the far end would cause a flashover of the wiring devices in the service panel [15]).

B. Shunt-Connected SPD Installations

The second experiment demonstrates the effect of installing a separate shunt-type SPD with long connections to a service panel. For practical situations, it is often postulated that the connecting leads can be represented by an inductance in the order of $1\ \mu\mathrm{H/m}$, while the resistance of these leads can be neglected. A connection involving 30 cm of leads, a typical length for a

[5]The measurements were conducted with calibrated instruments but some variability occurs in successive shots. The differences observed for the different span values exceed uncertainties, so that any uncertainties will not affect the conclusions.

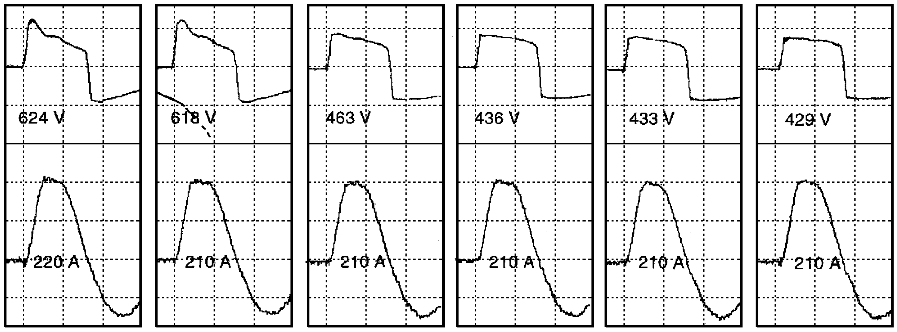

Fig. 8. Induced voltage with injected Ring Wave.

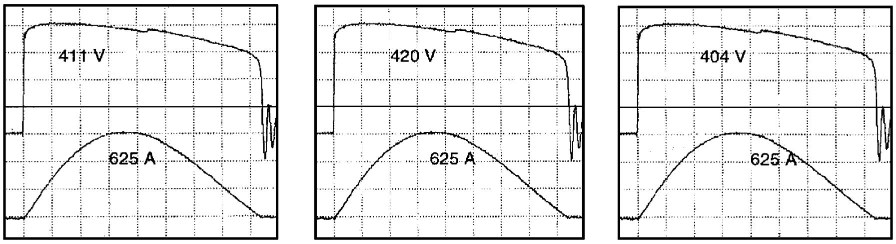

Fig. 9. Induced voltage with injected Combination Wave.

careful installation of a shunt-connected SPD,[6] could add several hundred volts to the limiting voltage achieved by the SPD itself in cases of high rates of current changes in the incoming surge.

SPDs packaged as power strips or plug-in inherently provide a two-port configuration on which the user has no control, but hopefully include internal wiring configuration that minimizes the lead effect. Furthermore, SPDs designed for integrated installation, such as a meter-base SPD or a panel plug-in SPD, offer a minimum of lead length, if the grounding lead is kept as short as possible (twisting leads to reduce the loop area or cancel the coupling is not a possible option in this case). On the other hand, in the case of separate SPDs permanently connected in shunt but located some distance from the point of connection, the length of that connection becomes quite significant, as our second experiment will show (nothing new about that), but also quantify.

Again, IEC 61 643-12 provides useful information on this subject, but its Fig. 10-c (redrawn here as Fig. 10) only states that twisting leads is an acceptable alternative when the *preferred* four-terminal configuration (Fig. 5) is not possible. In our second experiment that we are about to describe, the connection of the SPD was made with the closely-spaced but not twisted pair of conductors encased in their plastic jacket. We did not attempt to twist the leads, being unaware of a potential significant reduction of inductance by twisting the closely-spaced pair (unlike sensitivity to external electromagnetic fields which, indeed, can be decreased by twisting leads). Instead, we went to another possibly greater reduction of inductance by using a coaxial cable connection, as we will describe later.

The experiment was conducted with a circuit as shown in Fig. 11, using a 20-m-long line of typical residential cable ($2+\mathrm{G}$ conductors, plastic jacket, 2.5 mm^2 or #12 AWG). The coaxial varistor was connected at the far end (right), and a Ring Wave was applied at the near end (left). With a constant generator setting and an unchanged line length, the surge current could be maintained at a constant amplitude and waveform, thus allowing direct comparison of the measured voltages. These voltages were measured for several distances "d" between the varistor and the point of connection of the probes. In an actual installation, this point of connection would be the service panel, and the cable length "d" between that point and the varistor would be the infamous "lead length" associated with a real-world installation. Fig. 12 (overleaf) shows the voltage measured for an ideal (but impractical) coaxial MOV, serving as baseline reference of the "true" limiting voltage, and the voltages measured for increasing values of the lead length.

Fig. 12 shows, from left to right, the voltages at the point of connection of the MOV (Vp) for increasing distances between this point of connection and the shunt-connected SPD, the idealized coaxial MOV in our experiment (upper trace). The lower traces document the constant value of the peak of the impinging

[6]Several IEEE and UL standards now being developed include a stipulation that the measurement of the limiting voltage shall be performed with a specified lead length. However, some of these measurements are specified for relatively low values of the surge current, making it more difficult to detect the significance of the linear increase for high surge currents.

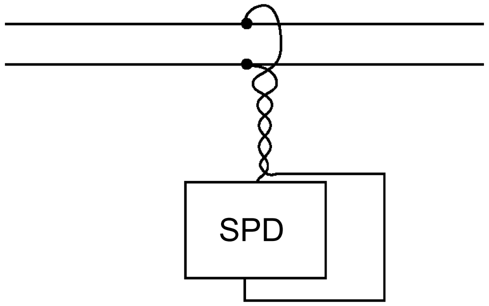

Fig. 10. Acceptable connection arrangement when four-terminal arrangement is not possible, per IEC 61 643-12.

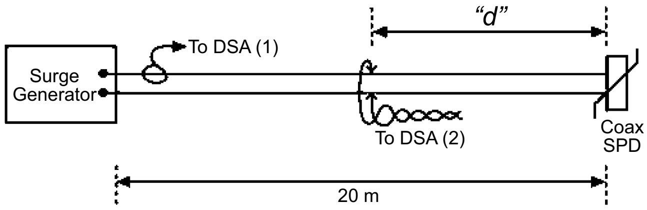

Fig. 11. Test circuit for assessing the effect of lead length.

surge current injected into the circuit. From left to right, compared to the baseline $(\mathrm{d} = 0)$ for a measurement made at the coaxial cable output of the MOV, the Vp caption shows the increase in the effective limiting voltage (decreased performance) that will be seen by the "protected" load. That increase is already 240 V for just 1 m of connecting leads and that type of impinging surge.

Some proposals have been made to decrease this adverse effect by using a coaxial cable to make the connection of the SPD package to the service panel. For the last oscillogram to the right of Fig. 12, a readily available 3-m length of an RG8 coaxial cable replaced the last 3 m of the plastic-jacket cable. Interpolating the readings on plain cable for $\mathrm{d} = 2$ m and $\mathrm{d} = 4$ m yields 1150 V (for a 3-m length of plastic jacketed cable), compared to the 960 V obtained for the coaxial cable connection.[7] While this might be seen as a significant improvement, it might not be large enough to justify the costs or the complication of a coaxial cable lead that would have to be installed by an electrician unfamiliar with methods of connecting such coaxial cables within conventional wiring.

The experiments reported here were conducted using real wiring but contrived configurations to illustrate the points being made. The applied surges were delivered by a generator producing "textbook" C62.41 waveshapes. Being injected in an inductive circuit, the actual surge current had a rise time of about 0.8 μs rather than the C62.41 value of 0.5 μs. Close examination of the original laboratory (larger) current traces of Fig. 12 revealed an actual maximum rate of rise of about 290 A/μs for a peak value of 220 A (about half the 500 A peak value of the Category B of C62.41). Such a rate of rise, applied to a connection of 1 m, and rule of thumb of 1 μH/m for the cable inductance, should produce a voltage drop of about 290 V. The difference in the observed voltages in Fig. 12 for $\mathrm{d} = 0$ m and $\mathrm{d} = 1$ m is 240 V, not quite the 290 V computed with the rule of thumb inductance value. Given the wide range of real-world rates of rise, this difference between the experimental observations and the rule-of-thumb computation does not affect the conclusions on the order of magnitude of the effect.

In the previously cited paper [15], the "gentle toe" concept was brought up: the theoretical waveforms, such as those used in numerical computations, can produce unrealistic values for the maximum rate of rise at the instant of the surge initiation. In the real world, surge currents do not have their maximum rate of rise at $t = 0$, but only some brief time after. Another difference between theory and reality is that most practical Combination Wave surge generators have an "undershoot"—a reversal of polarity in the surge current—after the theoretical unidirectional impulse. This polarity reversal is further enhanced by the inductance of practical circuits, as opposed to the dead short postulated in the definition of the short-circuit current of the Combination Wave. Consequently, for modeling purposes, many researchers use a damped sine wave instead of the standard unidirectional wave (Hasse *et al.* [16]). However, this damped sine wave has its maximum di/dt at $t = 0$ (the derivative of the sine is a cosine); hence, the "gentle toe" idea to reconcile theory and reality.

For instance, Table I, first compiled in the cited paper [15], shows the maximum values of di/dt for three different nominal rise times of a damped sine wave with a 5 kA peak. It is noteworthy that the relationships are not linear, and that the maximum di/dt is greater than the value that one would obtain by simply dividing the rise time into the peak value, a fact that is sometimes overlooked in oversimplified discussions. These more realistic values of di/dt can then be combined with the empirical 1-μH/m value of the connecting leads to estimate the degradation resulting from an excessive lead length.

IV. CONCLUSION

These experiments have clearly demonstrated that focusing exclusively on the "lead length" for SPD installations can lead to misconceptions or unwarranted expectations, such as the "four-terminal SPD" configuration. On the other hand, a quantitative assessment of the effect of long connections of a shunt-type device will provide useful guidance on installation practices.

1) While there is merit in the concept of a four-terminal shunt SPD, the benefits can be greatly degraded if proper attention is not given to the lead configuration. Just using a four-terminal device will not ensure optimum performance.
2) Improper installation of a separate shunt-type SPD via a "long" connecting cable to the service panel will degrade the performance in case of high rates of current changes in the impinging surge (in particular those implied for some commercial packages that propose ratings of tens of thousands of amperes). In the case of more moderate reasonable rates of change, this effect might have been somewhat overemphasized in the literature.

[7]In case our readers would wonder why we used a 3-m length of cable rather than 2 or 4 m, that would allow a direct comparison with the plastic-jacket cable (or a conduit-enclosed set of single wires as used in commercial installations), this last experiment with the coaxial cable connection was an unplanned last-minute addition to the test and was improvised by using an available cable borrowed from other equipment, for which the careful terminations could not be tampered with; hence, the nonnegotiable 3-m length—a further illustration of the inconvenience of making coaxial cable connections in the field.

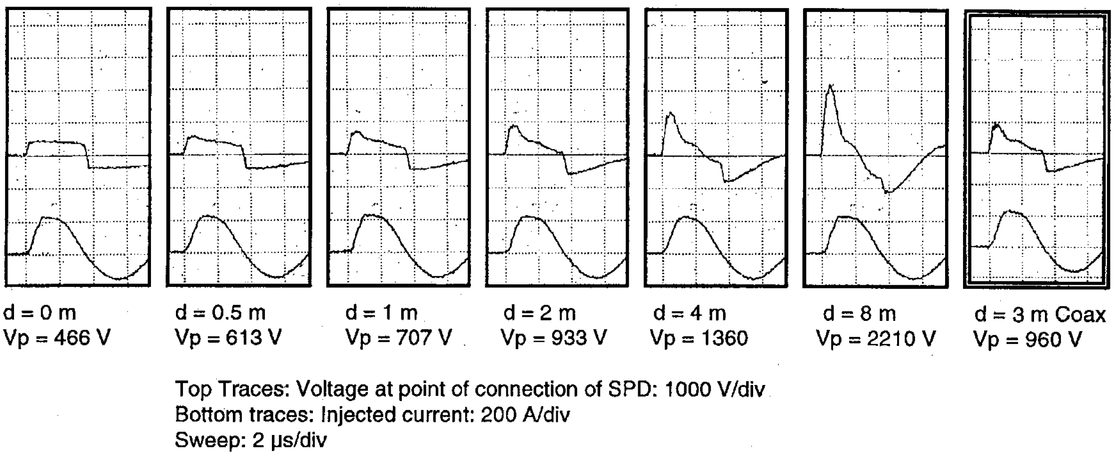

Fig. 12. Effect of SPD connection length on the protective level of downstream loads.

TABLE I
RELATIONSHIP BETWEEN NOMINAL RISE TIME AND MAXIMUM RATE OF CURRENT RISE FOR A 5000-A PEAK SURGE CURRENT

Nominal rise time, µs	5	10	20
Maximum *di/dt*, A/µs	1250	850	630

3) Attention should be given to the lead configuration as well as to lead length. For instance:
   - For a separately-mounted one-port SPD, twisting the leads or using a coaxial cable between their point of connection to the protected circuit and the SPD package will reduce the inductive coupling but not greatly reduce the inductance of the connection. Lead length remains a significant factor.
   - For one-port SPD packages that are mounted inside or on the side of a panel, an arrangement that provides a minimum of lead length, twisting leads (if possible) will help reduce inductive coupling.

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François D. Martzloff (M'56–LF'94) is with the National Institute of Standards and Technology (NIST), Gaithersburg, MD, where he has continued his pursuit of transients. He had 32 years of experience in the private sector [Southern States Equipment (Hampton, GA) and General Electric], before joining NIST in 1985.

As technical contributor, editor, and working group chair, he contributed to several IEEE, IEC, and UIE standards and guides, and has published many research and tutorial papers (such as the present one) on the application of surge-protective devices and power quality.

Kermit Phipps (M'95) is with EPRI PEAC, Knoxville, TN, where he is involved in electromagnetic-compatibility (EMC) test programs in accordance with standards of the IEEE, IEC, U.S. Military, and UL, as well as with the EPRI System Compatibility Protocols. He served in the U.S. Air Force before joining EPRI PEAC.

He has authored several papers on surge protection and SPD applications, and has conducted a number of power quality training sessions and field investigations.

Mr. Phipps is Chair of the P1560 Filter Measurement Standard and Secretary of the IEEE EMC TC-4 Working Group.