The Fallacy of Monitoring Surge Voltages: SPDs and PCs Galore!

Arshad Mansoor and Kermit Phipps
EPRI-PEAC
10521 Research Dr.
Knoxville, TN 37932

François Martzloff
National Institute of Standards and Technology [1]
Gaithersburg MD 20899-8113

Abstract

To support the recommendation of shifting transient monitoring from voltage surges to current surges, the paper presents experimental results as well as numerical modeling results demonstrating two mechanisms causing an apparent decrease of surge activity in low-voltage ac power circuits. The first mechanism is the proliferation of surge-protective devices, a situation which is by now well recognized. The second, which should also have been recognized, apparently escaped scrutiny so far: the proliferation of electronic appliances containing a switch-mode power supply that effectively places large surge-absorbing capacitors across the ac power systems.

1. Introduction

This paper is unabashedly tutorial, and some of the themes presented here might be quite familiar to some of our readers. However, we have observed that these concepts, which could almost be characterized as obvious when given the benefit of hindsight, are still not widely recognized. Therefore, we will present them to this forum, and illustrate their validity by experimental measurements and numerical modeling. The three major themes of this presentation are:

1. There is a logical explanation for the apparent decrease in the level of voltage surges reported in recent power quality surveys: the proliferation of surge-mitigating devices.
2. The present practice of recording voltage surges can lead to erroneous concepts on surge protection, which in turn can lead to equipment failures.
3. There is an unfulfilled need to develop and deploy power quality monitors that can characterize the energy-delivery capability of a surge event.

The first theme will be introduced by a historical perspective showing how *voltage* surges became the focal point of monitoring surges, even before the term "power quality" was coined. Experimental measurements and numerical modeling will be described to illustrate the effect of the proliferation of surge-protective devices (SPDs) and of new electronic appliances that serve respectively as intended and unintended surge-mitigating devices. The next two themes will be only briefly discussed because, once the first is accepted, these two follow quite logically.

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1 *Electricity Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce.*

2. Historical Perspective

The proliferation of SPDs in low-voltage ac power circuits has been recognized as one of the root causes of the apparent decrease of the surge levels recorded in recent power quality surveys. The change in the occurrence of surges began to be recognized [Dorr, 1995] [1] and explanations were offered attributing the phenomenon to the emerging proliferation of SPDs in low-voltage ac power circuits [Martzloff, 1996]. It is noteworthy that for many people, the term "surge" is equivalent to "transient overvoltage" to the point that the phenomenon has generally been recorded by instruments acting as voltmeters, and the term was without much scrutiny accepted in general as meaning a voltage surge.

For instance, in the bi-lingual publications of the International Electrotechnical Commission (IEC), the French text which parallels the English text uses the term "surtension" (meaning overvoltage), because there is a mind set, reinforced by the lack of a neutral term in French that could be applied to either or both voltage surges and current surges. In the United States, the Underwriters Laboratories perpetuates this narrow perspective by calling SPDs "Transient *Voltage* Surge Suppressors" (italics ours) [UL Std 1449, 1996], although both recent IEC and IEEE definitions of SPDs introduce and emphasize the concept of ***current surges*** as well as ***voltage surges***.

Now less recognized but significant, a similar cause for the apparent decrease of voltage surge levels is becoming important as more and more electronic appliances depend on a switch-mode power supply with a rectifier-capacitor DC link. Through the rectifier, the DC link capacitor which is typically in the order of 200 µF to 500 µF, offers a low-impedance path to current surges impinging on the power port of these appliances. With many such appliances connected in an end-user installation, the effect is that of quite a large capacitor being connected across the ac mains. Small wonder then that even large ***surge currents*** (for instance, with the capability of delivering currents of 3 kA, 8/20 µs) [ANSI/IEEE C62.41-1995] can no longer raise the voltage across the mains to the high values sometimes reported in earlier surveys of ***surge voltage*** occurrences.

Another historical mind-set has been to recognize the origin of surges only as a voltage event while in fact it can be either a true induced-voltage event, or the end-result of the injection of a surge current somewhere in the power system. Typical induced-voltage surges are associated with the electromagnetic coupling into the power circuits of the field created by a nearby (but not direct) lightning flash. Such voltage surges, which can develop substantial voltages in high-impedance circuit loops [Martzloff et al., 1995] can easily be mitigated with relatively small SPDs because their energy-delivery capability is relatively small [IEC document 64/1034/CD, 1998]. In contrast, current surges are produced either by the dispersion of the current associated with a lightning flash when a direct strike injects current at some point of the power system, in close vicinity or at a more remote point of the power distribution system [Mansoor et al., 1998]. Another source of current surges is switching surges involving the injection of residual energy into parts of the power system. The energy-delivery capability of these current surges can be substantial, and be a threat to the survival of improperly sized SPDs. Note in passing the use of the term "energy-delivery capability" and not "energy in the surge." Some of our readers are by now familiar with that theme [Lindes et al., 1997] — perhaps even tired of seeing it repeated — but the sad truth is that usage of the term "surge energy" is still rampant.

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1 *Citations appearing in the text as [Author, date] are listed in alphabetical order in Section 7, Bibliography.*

The significance of making the distinction between recording current surges versus recording voltage surges is very important for equipment designers. A decision to provide only modest surge withstand capability for an SPD incorporated at the power port of the equipment might be made because the contemporary surveys reveal few and moderate (voltage) surges. When combined with the misconception that "the lower the clamping voltage, the better" [Martzloff et al., 1989], the result can be disastrous. We have in our laboratory 'morgue' two examples of such mass-produced devices incorporating an inappropriate SPD that led to early mortality of the product. Without identifying the culprit — perhaps a harsh word for a designer who was lulled into this position by referring to misleading reports on surge activity — but to illustrate the situation, we can name the two products: a compact fluorescent bulb, and a remotely-controlled ceiling fan. To recite a recurrent theme in our tutorial presentations ("Transients Are Here to Stay"), voltage surges might appear to have faded away, but current surges are still here, ready to destroy a small SPD incorporated in a design based on the misperception of fading voltage surges, fostered by recording only voltage surges.

3. Experimental Measurements

To illustrate the effect of nonlinear SPDs as well as linear capacitors connected across the mains, the Power Electronics Applications Center (PEAC) "Upside-Down House" [Key et al., 1994] was used to inject surges into the service entrance of the Upside Down House with various combinations of SPDs and/or personal computer (PC) power supplies connected at the end of two branch circuits, one 9-m long, the other 36-m long. In Figure 1, currents in the branches and voltages at the nodes are identified respectively as I_s, I_9, I_{36}, and V_0, V_9, V_{36}. The charging voltage setting of the Combination Wave surge generator was kept constant to provide a 2 kV, 1.2/50 µs open-circuit voltage (OCV). In a second series of experiments, the setting was increased to 4 kV. This second series, not reported here in detail because of limited space, confirmed the expected nonlinear response of varistors and the linear response for capacitors only.

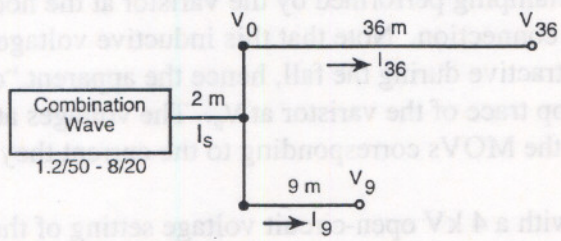
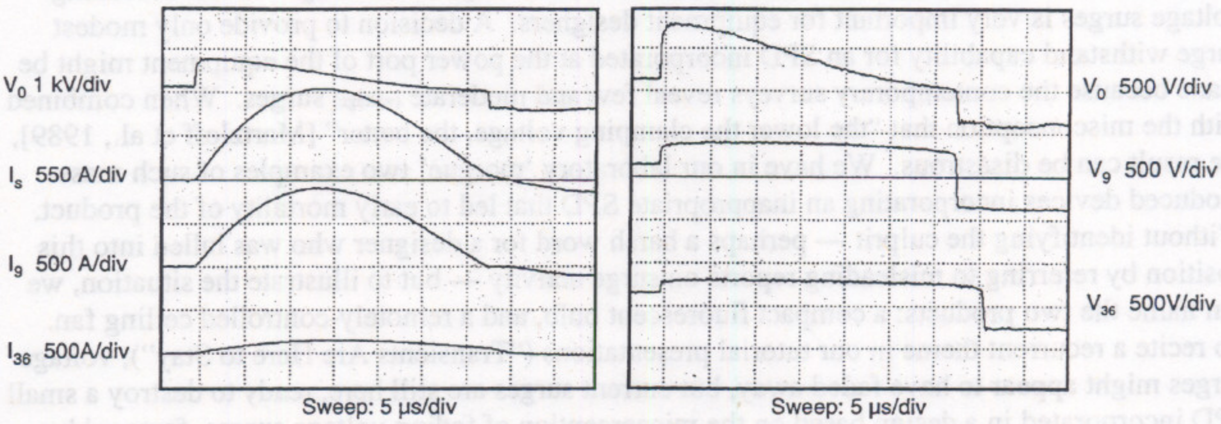


Figure 1 - Upside-Down House branch circuits

3.1 Metal-oxide varistors only

Given the known and predictable behavior of multiple SPDs — often reported in the literature to the point that bibliographic citations would take several lines to list all of them — this part of the experiment was performed only to provide a baseline. Metal-oxide varistors (MOVs) rated 150 V, 20 mm diameter, were used for this experiment. To record all interesting currents and voltages, two shots are necessary when using the 4-channel digital signal analyzer; therefore each oscillogram in the figures contains the trace of V_0 to serve as a common reference (Figure 2).



Currents in branches

V_0 (peak V)	I_s (peak A)	I_9 (peak A)	I_{36} (peak A)
790	1000	900	150

Voltages at nodes

V_0 (peak V)	V_9 (peak V)	V_{36} (peak V)
790	410	330

Figure 2 - Typical recordings[1] made during the first experiment — SPDs only.

In Figure 2, the current traces (left oscillogram) show the unequal sharing between the two MOVs, reflecting the difference in the inductance of the two branch circuits. Because the peaks of the two branch-circuit currents are not simultaneous (the current in the longer branch circuit takes longer to build up) their sum seems to exceed the peak of the injected current, I_s.

The voltage traces (right oscillogram) show how the voltage at the service entrance, V_0, is mitigated from the 2 kV open-circuit voltage supplied by the generator that would propagate without attenuation in the absence of a surge-mitigating device [Martzloff et al., 1986]. This voltage V_0 is the sum of the clamping performed by the varistor at the node V_9, and the inductive voltage drop in the 9-m long connection. Note that this inductive voltage is additive during the rise of the current I_9, and subtractive during the fall, hence the apparent "overshoot" in the trace of V_0, compared to the flat-top trace of the varistor at V_9. The voltages at V_9 and V_{36} are the typical clamping voltages of the MOVs corresponding to the current they carry.

In a subsequent experiment with a 4 kV open-circuit voltage setting of the generator (twice the value of Figure 2, but not reported here in detail because of limited space), the voltages across the varistors, predictably, were not substantially increased. However, the substantially increased current in the 9-m long branch circuit (from 1000 A to 2800 A, resulting from the nonlinear response of the varistor) produced an increased inductive effect to the point that the voltage at the service entrance was raised to 1300 V from the 790 V recorded for the case of Figure 2. Table 1, at the end of this section, presents a summary of the peak values recorded in the various combinations of components, branch circuits, and amplitudes of the injected surge.

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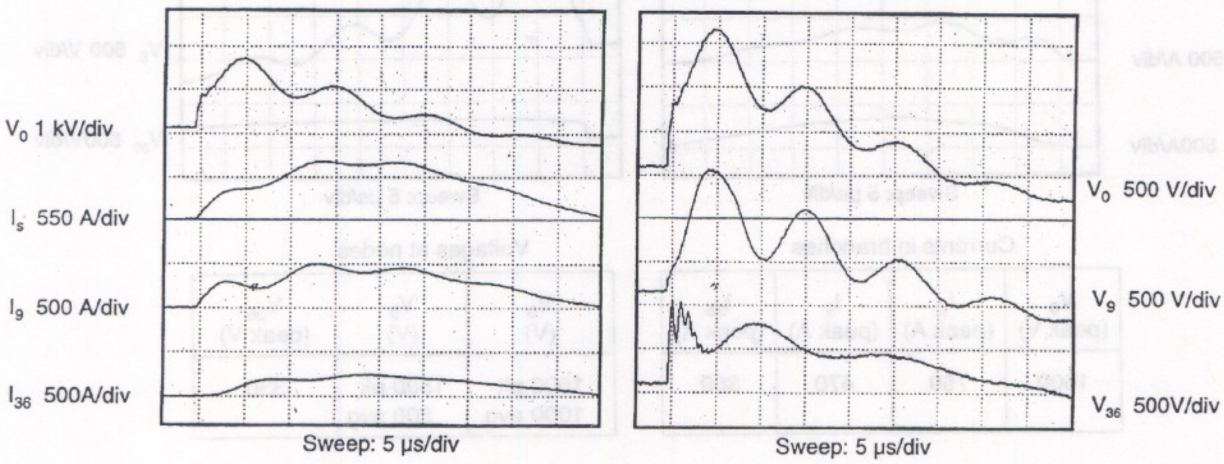
[1] *The experimental values shown in Figures 2, 3, and 4, and in Table 1 were recorded with a digital signal analyzer. They have been rounded off to the nearest ten to convey a simpler set of numbers, uncluttered by a precise last digit. Uncertainty in these measurements is not an issue here as it does not affect the general conclusions.*

3.2 Capacitors only

In a second set of experiments, less easily predictable would be the behavior of the still all-linear circuit involving the capacitors of a PC power supply (440 μF each in this experiment) when receiving a surge originating from the complex RLC wave-shaping network of a Combination Wave surge generator (Figure 3).



Currents in branches

V_0 (peak V)	I_s (peak A)	I_9 (peak A)	I_{36} (peak A)
1700	690	510	250

Voltages at nodes

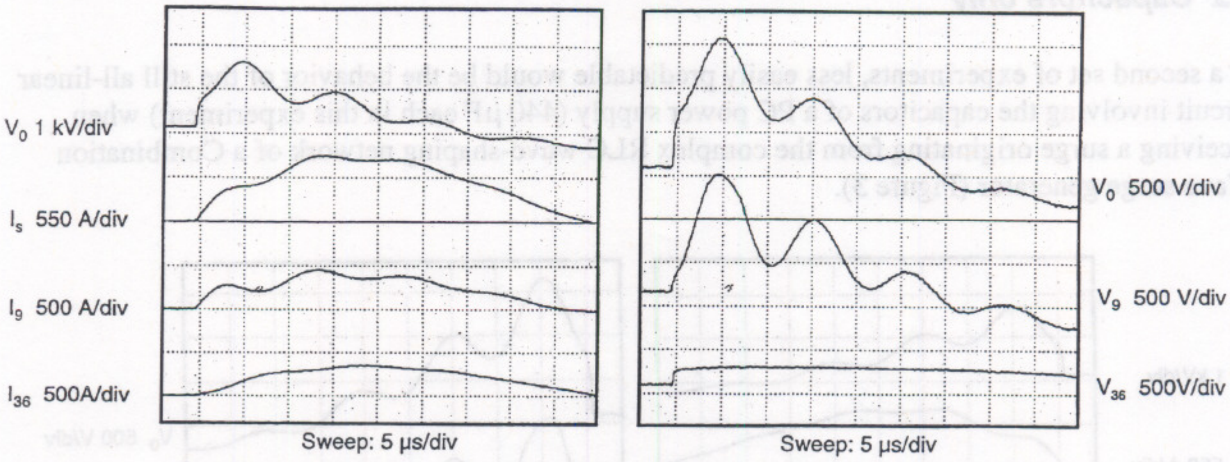
V_0 (V)	V_9 (V)	V_{36} (V)
1700 pk 1300 avg	1500 pk 1000 avg	1000 pk 600 avg

Figure 3 - Typical recordings made during the second experiment – Capacitors only

In Figure 3, the voltage at the service entrance, V_0, is mitigated from the 2 kV open-circuit voltage supplied by the generator. However, because of the interaction between the RLC components in the wave-shaping network of the Combination Wave generator on the one hand, and the capacitances of the PC power supplies and inductances of the branch circuits on the other hand, this voltage rings around an average voltage level of 1300 V, reaching a peak of 1700 V. To reflect this situation, the tabulation of the voltages in the figure shows two lines, peak and average. Thus, the mitigation effect is degraded by the ringing. Nevertheless, one can expect that as more PCs would be added, the ringing frequency would become lower and the voltage peaks lower.

3.3 Capacitor and MOV

In a third set of experiments, a capacitor was connected at the end of the 9-m branch circuit and an MOV was connected at the end of the 36-m branch circuit. Interest in this particular configuration was motivated by the desire to show how an MOV would mitigate the ringing that was observed in the preceding experiment at the end of the 36-m line (V_{36} in Figure 3).



Currents in branches

V_0 (peak V)	I_s (peak A)	I_9 (peak A)	I_{36} (peak A)
1600	769	470	360

Voltages at nodes

V_0 (V)	V_9 (V)	V_{36} (peak V)
1600 pk 1000 avg	1500 pk 800 avg	330

Figure 4 - Typical recordings made during the third experiment – capacitor and MOV.

Experiments 2 and 3 (Figures 3 and 4) do show decreasing levels of voltage surges at various points of the Upside Down House, compared to the open-circuit conditions. However, the interactions between the capacitors of the generator RLC wave-shaping network on the one hand, and the PC capacitors on the other hand, make detailed interpretation of the waveforms tedious and beyond the scope of our illustrative examples. Numerical modeling with a current source, as reported in the following section, avoids this interaction and provides further evidence on the "PCs Galore" effect. For readers interested in the details, Table 1 documents the results concerning peak voltages noted from the oscillograms kept on file but not reproduced here. Readers interested primarily in the big picture may skip a close examination of this table.

Table 1 - Summary of node voltages for component combinations

Detailed experiment description number	Device Combination		Voltages for 2 kV OCV (peak V)			Voltages for 4 kV OCV (peak V)		
	9 m	36 m	V_0	V_9	V_{36}	V_0	V_9	V_{36}
	Open	Open	2500	2600 *	3300 *	Not done (linear)		
		MOV	1700	330	1900 *	1300	400	370
		Capacitor	1800	1900 *	1300	Not done (linear)		
	MOV	Open	860	400	1300 *	1400	400	2000 *
3.1 - MOVs only		MOV	790	410	330	1300	390	400
		Capacitor	720	420	700	1300	390	990
	Capacitor	Open	2000	1600	2100 *	Not done(linear)		
3.3 - Capacitor and MOV		MOV	1600	1500	370	Capacitor failed, end test		
3.2 - Capacitors only		Capacitor	1700	1550	1100	Not done (linear)		

* Ringing at the open-ended line is the cause of this voltage being greater than V_0.

4. Numerical Modeling

Our previous experience with modeling cascaded SPDs [Lai et al., 1993] and the behavior of the Upside Down House with installed SPDs [Martzloff et al., 1995] can be readily applied to the prediction of the behavior of the three circuits subjected to the experimental measurements, with an imposed current source, free from the unavoidable interactions that occurred in the preceding experimental measurements. This approach yields the best of the two methods: a computation that has been well demonstrated as suitable for modeling nonlinear SPDs, and the freedom to impose any fixed waveform — what reality imposes on a residence is not the surge from an impedance-limited surge generator — combined with the possibility to model many branch circuits and many combinations of SPDs and/or capacitors.

4.1 Modeling combinations of loads and branch circuit lengths

In a series of modeling runs similar to the combinations of the experimental measurements, the model used the circuit of Figure 5. A current source feeds a fixed current surge via a common service drop to the panel bus of the service entrance, where three branch circuits made of 2-mm diameter conductors (#12 AWG) take off, with length of respectively 5 m, 10 m, and 20 m. The choice of these lengths was based on curiosity about the effect of the long distance connection (and thus an effect that might be delayed or degraded) to the immediate occurrence of an overvoltage at the end of shorter branch circuits. The currents in the circuit are identified in Figure 5 respectively as I_s, I_0, I_5, I_{10}, and I_{20}, with the node voltages at the service bus and branch circuit ends respectively as V_0, V_5, V_{10}, and V_{20}.

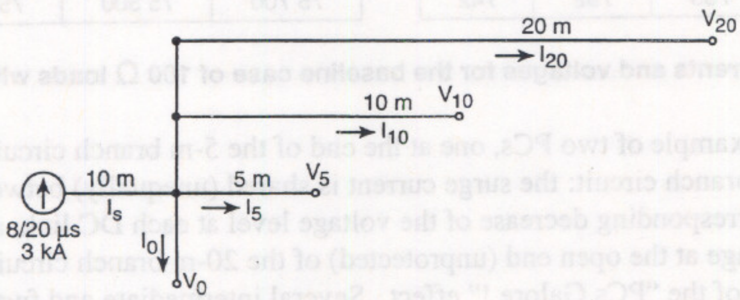
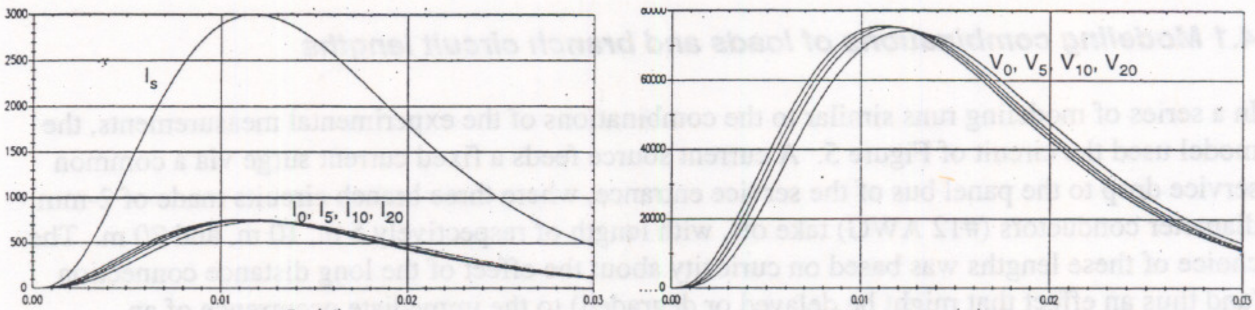


Figure 5 - Service drop and branch circuits for modeling combinations

As in our previous modeling applications, the EMTP program [EPRI, 1989] was used. To avoid computational artifacts, a finite 10 kΩ resistance was always postulated at the ends of all branch circuits, whether these were left in "open" or "loaded" condition. The loads that were modeled included combinations of SPDs, capacitors, and 100 Ω resistors. The SPDs were all 20-mm diameter, 130-V rated MOVs. The capacitors included a capacitance of 440 µF and a series resistance ("ESR") of 0.25 Ω to represent an electrolytic capacitor. Initial conditions for the models stipulated an initial charge on the capacitor to represent the normal condition of the DC link. The 100 Ω resistor was selected as a typical value for a 150-W power-consuming appliance connected at the end of the branch circuit.

Just to illustrate the point of a readily predictable behavior of a purely linear circuit, Figure 6 shows the voltages and currents for the case of 100 Ω loads confronted with a current source. Compared with the 100 Ω load at the end of the branch circuits, the series impedance has a very small effect and the impinging surge current I_s divides almost equally (3000 A /4 = 750 A) in the nearly identical four branches I_0, I_5, I_{10}, and I_{20} (I_0 being the current in the service entrance 'branch', with a length of 0). Thus, the voltage developed by this 750 A current across 100 Ω would simply be expected to be 75 000 V (seventy five thousand volts). We say "would be expected" because, of course, the insulation level of a real-world low-voltage insulation cannot withstand such a voltage. The result of this theoretical case is another illustration of the theme "More Begets Less," according to which a high-amplitude, steep-front surge cannot propagate in branch circuits because a flashover will occur at the origin [Mansoor et al., 1998].



Currents in branches: Time in milliseconds, peaks in amperes

I_s	I_0	I_5	I_{10}	I_{20}
3000	757	755	752	742

Voltages at nodes: Time in milliseconds, peaks in volts

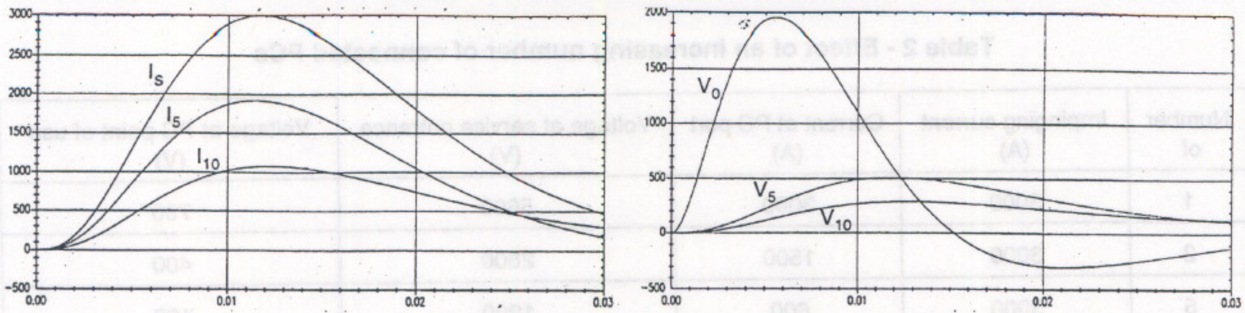
V_0	V_5	V_{10}	V_{20}
75 700	75 500	75 300	74 200

Figure 6 - Currents and voltages for the baseline case of 100 Ω loads without SPDs

Figure 7 shows the example of two PCs, one at the end of the 5-m branch circuit, the other at the end of the 10-m branch circuit: the surge current is shared (unequally) between the two capacitors, with a corresponding decrease of the voltage level at each DC link, and also a reduction of the voltage at the open end (unprotected) of the 20-m branch circuit. This example shows the beginning of the "PCs Galore !" effect. Several intermediate and further steps were modeled by adding combinations of surge-mitigating devices to build our case file and confirm the expected effects, but we will spare the reader from a tedious recitation.

The results shown in Figure 6 call for several comments:

- The unequal division of the currents I_5 and I_{10} reflects the effect of the larger impedance of the 10-m branch circuit, compared to the 5-m branch circuit.
- Substantial mitigation is obtained at the nodes V_5 and V_{10}, as a result of the filter-like action of the line inductance and the capacitance of the PC power supply.
- The voltage surge developed at the node V_0 propagates, unabated, to the end of the open-circuited 20-m branch circuit, a reminder that the notion of voltage surges being attenuated as they propagate in building wiring [IEC Report 664, 1980] was incorrect.



Currents in branches: Time in milliseconds, peaks in amperes

Voltages at nodes: Time in milliseconds, peaks in volts

I_s	I_0	I_5	I_{10}	I_{20}
3000	0	1920	1080	0

V_0	V_5	V_{10}	V_{20}
1960	507	290	1960

Figure 7 - Currents and voltages for the case of two PCs without SPDs

The voltage results are especially worth noting, in the context of what a power quality monitor would report in such an installation, depending upon its point of connection.

- From the (impossible) high voltages of the 100 Ω baseline (no SPDs), the voltage that would be recorded by a monitor installed at the service entrance is now reduced to "only" 1960 V.
- A ***voltage-only monitor*** installed at the point of use of the power (typical selection of point of installation in many surveys), namely the two receptacles at 5 m and 10 m feeding the PCs, would report respectively 510 V and 290 V, ***creating the illusion (fallacy) that there is no significant surge activity*** at these points.
- In reality a current surge I_5 of nearly 2000 A is carried by the PC rectifier into the capacitor, via a line fuse. Such a high current — ***undetected by a voltage-only monitor*** — could very well be fatal for the rectifier or the input fuse, or for the capacitor of the PC power port. Such failures were found in post-mortems of equipment recently performed at PEAC. That scenario is also what occurred in the experimental test of Section 3 for a 4 kV open-circuit voltage and capacitor-MOV combination (shown in next-to-last row of Table 1).

4.2 Modeling PCs Galore

As a grand finale for illustrating our major theme, the case of an increasing number of PCs was modeled, with each of the PCs connected at the end of a dedicated branch circuit, with all branch circuits having the same length of 20 m, still with the 10-m long service drop driving a 3 kA current surge into the installation.

Table 2 shows the resulting voltages at the service entrance and at the point of connection of the PCs, as well as the imposed impinging current and the resulting currents in the individual power ports of the PCs. Indeed, the effect is linear with increasing numbers of PCs, and the resulting decrease in the voltages expected to be reported by a power quality monitor installed at the point of use is quite apparent.

Table 2 - Effect of an increasing number of connected PCs

Number of	Impinging current (A)	Current at PC port (A)	Voltage at service entrance (V)	Voltage at PC point of use (V)
1	3000	3000	5600	790
2	3000	1500	2800	400
5	3000	600	1200	160
10	3000	300	570	79

Inspection of the table shows that the effect is practically proportional to the number of PCs in use in the installation. While we have used the short acronym of PC in the title and preceding discussions, the proliferation that we observe is not limited to PCs, but includes many electronic appliances, such as home entertainment, heating and air conditioning with adjustable speed drive, that use a DC link with large energy-storage capacitor.

5. Action Items

The customary closure of a paper is to list conclusions. However, in this case we suggest action items for industry, rather than academic conclusions:

- The examples given here clearly show that the fallacy of little surge activity can be created by limiting power quality measurements to voltage surges. With undetected current surge activity, users of electronic appliances will be puzzled by unexplained failures in the face of reports of little voltage surge activity.
- We offer the explanation that these unexplained failures are likely to be associated with the (heretofore not characterized) surge current delivery capability of the environment. Such failures could have been avoided, had designers been better informed.
- With our leading theme now solidly established, questions arise about what to do about it. This matter requires the dedicated attention of both manufacturers and users of power quality monitoring instruments.
- Unfortunately, more than three years after beginning the crusade to overcome the fallacy of limiting surge measurements to voltage surges [Martzloff, 1995], there is no commercially available power quality monitor capable of characterizing the energy-delivery capability of a surge event.
- Worse yet, among the international delegates to an IEC working group chartered to develop a standard on measurement of power quality parameters (which is likely to dominate the design of future monitoring instruments), there are some claims being made that "a current surge is not a power quality parameter" and therefore it should not be included in the emerging standard prescribing measurements methods. This misconception needs to be corrected.
- Therefore, the crusade must be pursued with perseverance, and it is the goal and hope of the authors that sufficient recognition of the fallacy will eventually create a market demand for appropriate instruments, which forward-looking manufacturers may have developed or may be in the process of developing in anticipation of such recognition.

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