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SURGE RECORDINGS THAT MAKE SENSE

Joule Deposition : Yes ! - "Joule Content" : Never !

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Abstract

This paper offers a rationale for avoiding attempts to characterize the surge environment in low-voltage end-user power systems by a single number -- the "energy in the surge" -- derived from a simple voltage measurement. Numerical examples illustrate the fallacy of this concept. Furthermore, based on the proliferation of surge-protective devices in low-voltage end-user installations, the paper draws attention to the need for changing focus from surge voltage measurements to surge current measurements.

Introduction

Sensible application of surge-protective devices (SPDs) requires that the capability of a candidate SPD be sufficient to absorb the energy that an impinging surge could deposit in the device. This eminently rational approach, however, was derailed when the erroneous concept was proposed that one could measure the "energy in the surge" and thus prescribe an easy match of the energy-handling capability of an SPD to the "energy" of its environment.

In a more recent approach by standard developers, an attempt was made to express this concept as a "specific energy" that would normalize it with respect to a postulated resistance of a device exposed to the impinging surge. Our thesis is that such attempts are neither realistic nor relevant. We will show that these erroneous attempts, based on the classical formula for computing the energy dissipated in a linear load of known resistance, cannot be applied to characterize the environment. There is no meaningful relationship between the "energy" in a surge event as derived (erroneously) from the single voltage measurement and the energy actually deposited in a varistor by this surge event.

Furthermore, the results obtained when recording ***surge voltages*** conducted since the mid-eighties have now become questionable as a result of the proliferation of surge-protective devices. It is very doubtful that a surge voltage monitor, installed in a typical end-user facility, will record anything but the residual voltage of unknown SPDs in the installation -- which is no measure of the threat of an incoming surge. Only a ***surge current*** measurement in a candidate SPD can assess the threat.

A review of equipment failure or upset mechanisms related to the occurrence of a surge voltage reveals that none of these mechanisms are related to this so-called "energy in the surge." Several failure mechanisms other than energy-related are identified, pointing out the need to describe the surge events with a more comprehensive set of parameters in conducting future surveys.

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The Fallacy of Joules Content

In an attempt to characterize the potential threat of surges to voltage-sensitive equipment, recordings of the surge voltages occurring in low-voltage power circuits have been conducted in the last quarter-century, driven by the increasing concern about the vulnerability of new electronic appliances to transient overvoltages. However, practically all the recording campaigns conducted by major organizations such as ERA (Bull and Nethercott, 1964)[1], General Electric (Martzloff & Hahn, 1970)[2], IBM (Allen & Segall, 1974)[3], Bell (Goldstein and Speranza, 1982)[4], Canadian Electrical Association (Hughes & Chan, 1995)[5], National Power Laboratory (Dorr, 1995)[6] and other researchers, including Hassler & Lagadec (1979)[7], Meissen (1983)[8], Wernstrom et al. (1984)[9], Goedbloed (1987)[10], Standler (1989)[11], and Forti & Millanta (1990)[12] have been limited to the measurement of transient ***voltages***.

Interest in these measurements has been re-kindled by several investigations aimed at assessing power quality in end-user facilities. These recordings, initially limited to measurement of peak voltages, were perfected with the help of increasingly sophisticated ***voltmeters***. Early surveys were conducted with conventional oscilloscopes; later on, portable digital instruments with on-board computing became available. While these instruments made possible the recording of a voltage transient as a function of time and graphical presentation of data, the recording of such a surge voltage profile does not lend itself to a simple description by a single number. To circumvent this difficulty, many researchers called upon the basic concept of energy to characterize the level of surge threat in terms of voltage. Referring to classical electrical engineering, the instantaneous power dissipated in a resistor by a transient voltage is merely the square of the applied voltage, divided by the resistance. Taking the integral over the duration of the transient yields the energy. By analogy, the "energy" of a surge could then be computed from the voltage measured at some point of a power system. According to this intuitive concept -- but fallacious as we will show -- the greater the measured voltage, the greater the "energy" and thus the greater the threat to potential victim equipment.

A review of the known failure or upset mechanisms of various types of devices and equipment identifies several surge parameters other than energy-related. These include source impedance, peak amplitude, maximum rate of rise, tail duration, and repetition rate. Thus, future surveys of surge events conducted with present or with even better monitoring instruments will need to include more comprehensive and hopefully standardized methods of presenting and interpreting the results.

Thesis

Our thesis is that neither the threat nor the "energy level" of a surge can be characterized by simply measuring the voltage change during a surge event. Any reference to the concept of "energy of a surge" should definitely not be introduced. Such avoidance is based on two facts:

1. A voltage measurement of the surge event cannot alone predict the energy levels affecting the devices exposed to that surge. This is particularly true for nonlinear surge-protective devices where energy deposited in the device is relevant, but has little to do with the misleading concept of "energy in the surge" derived from an open-circuit voltage measurement.
2. There are other than energy-related upset or failure modes of equipment. These effects require consideration of other parameters when describing a surge event to yield relevant and realistic assessment of surge stress threats.

This thesis will be supported by an analysis of the impact of surges on equipment, and illustrated by numerical examples of varistor applications showing how the description of a surge by its "energy" could then lead to vastly different conclusions.

Interactions Between Surges and Victim Equipment

At this point, we need to identify the devices and equipment that may become the victims of a surge, and their failure mechanisms. After-the-fact investigations and experimental data show a wide range of surge-related upset and failure mechanisms. These include insulation breakdown, flashover, fracture, thermal and instantaneous peak power overloads, dv/dt and di/dt limits being exceeded. The following list gives some generic types of surge victims and the typical failure or upset mechanisms. It is highly significant that in all this list, the term $[v^2 \times dt]$ or its integral does not appear. Table 1 provides a summary of this list of victims and relevant surge parameters associated with the failure modes.

1. ***Electrical insulation***, where the failure mechanism (breakdown or sparkover) is principally a function of the surge voltage, with the complication of a volt-time characteristic such that failure under impulse occurs at a level that increases when the rise time or duration of the impulse decreases. "Insulation" is to be taken in the broadest sense of solid or liquid material separating energized conductors in equipment, clearances on a printed circuit board, edges of semiconductor layers, etc. A distinction must be made between the initial breakdown of insulation, related to voltage only, and the final appearance of the damaged insulation, related to the total energy dissipated in the breakdown path. In another situation, the insulation of the first turns of a winding may be subjected to higher stress than the others as the result of the uneven voltage distribution resulting from a steep front rather than only the peak value of the surge.

2. ***Surge-protective devices***, for which the voltage across the device is essentially constant, and the energy deposited is a function of the surge current level and duration. One failure mode of such a device will occur when the energy deposited in the bulk material raises the temperature above some critical level. Failure modes associated with the current level, such as flashover on the sides of a varistor disc, failure at the boundary layers of the varistor grains, or fracture of large discs, have also been identified and are not directly related to energy.

3. ***Semiconductor devices***, such as thyristors responding to the rate of voltage change can be turned on by a surge[13], resulting in failure of the device or hazardous energizing of the load they control. In a similar way, a triac may be turned on by a voltage surge without damage, but still fail by exceeding the peak power limit during a surge-induced turn-on with slow transition time.

4. ***Power conversion equipment***, with a front-end dc link where the filter-capacitor voltage can be boosted by a surge, resulting in premature or unnecessary tripping of the downstream inverter by its own on-board overvoltage or overcurrent protection schemes.

5. ***Data-processing equipment***, where malfunction (data errors) -- not damage -- may be caused by fast rate of voltage changes (capacitive coupling) or fast rate of current changes (inductive coupling) that reflect the initial characteristic of the surge event. This response is insensitive to the "tail" of the surge, where all the "energy" would be contained according to the misleading energy-related concept.

6. ***Light bulbs***, which of course have a limited life associated with filament evaporation and embrittlement -- a long-term process where the short burst of additional heating caused by a few microseconds of overcurrent is negligible -- but also fail under surge conditions when a flashover occurs within the bulb, triggering a power-frequency arc that melts out the filament at its point of attachment -- another failure mechanism originating with insulation breakdown.

Among these types of victims, only the clamping-type varistor is directly sensitive to an energy level associated with a surge event -- and at that, the energy deposited in the device, not the "energy in the surge." Considering the explosive proliferation of varistors, however, one might find some extenuating circumstances in emphasizing the significance of energy in describing the effect of surges on its principal target -- the ubiquitous metal-oxide varistor -- but this is a pitfall, a mental trap.

Table 1
Significant Surge Parameters (X) in Equipment Failure Modes

Type of equipment		Surge parameters					
		Source impedance	Peak voltage amplitude	Maximum rate of voltage rise	Tail duration	Repetition rate	I^2t in device*
Insulation	- Bulk		X		X **		
	- Windings		X	X			
	- Edges		X	X			
Clamping SPDs	- Bulk	X	X		X	X	X
	- Boundary		X		X		
Crowbar SPDs		X		X	X	X	X
Semiconductors	- Thyristors		X	X			X
	- Triacs	X	X	X			X
	- IGBTs		X	X			X
Power conversion	- DC level	X	X		X	X	
	- Other			X	X		
Data processing malfunction			X	X		X	

* The I^2t in the device is actually the result of the combination of surge parameters and device response to the surge. Like other power and energy-related equipment stress, I^2t is not an independent parameter of the surge.
** Amount of final carbonization, not the initial breakdown.

Baiting The Trap

From the interactions described above, it is clear that using a single voltage measurement to determine surge threat is not sufficient. The trap was baited by the simplicity and ease of using a single parameter obtained by analogy with the power dissipated in a fixed resistance, v^2/R by an instantaneous voltage, v. Clearly in that limited case, the total energy involved over the surge event would be the time integral of v^2/R, expressed by a number having the same dimensions as watt-seconds, or joules in the SI system. And thus some power quality monitors placed on the market in the early eighties were printing out surge event characterizations expressed in joules. This "joule" number was obtained by computation of the $\int v^2/R.dt$, where the voltage v was measured by the instrument, divided by a resistance (taken arbitrarily as 50 Ω), and integrated over the duration of the event. Manufacturers of power quality monitors soon recognized the potentially misleading aspects of such reporting and discontinued the practice.

Nevertheless, some researchers continued the practice and are to this day attempting to characterize the surge environment by the single parameter of "energy in the surge." As a half-way measure, some are now proposing a new parameter "specific energy" to be understood as the integral of voltage-squared divided by a reference resistance of 50 Ω (why that particular value ?) and they would report results in watt-seconds. Figure 1 shows an example of this type of reporting[14].

We completely agree that, indeed, the selection of an appropriate varistor should reflect the level of threat to which it will be exposed, so that there is a need to characterize the threat in terms of the energy that will be deposited in the varistor by a specific surge event. However, ***there is no way that a voltmeter measurement only, even if it includes time, can provide that information.*** This observation was presented at an earlier Power Quality Conference[15], and discussions in that forum, as well as in working groups developing standards on the surge environment, indicated the need to give a wider distribution to the message, hence this paper in this forum.

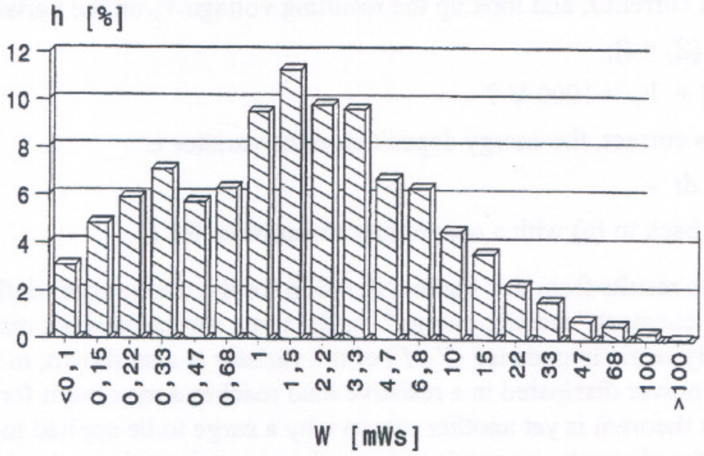

Figure 1 - Example of report of survey results [14] with number of occurrences as a function of "energy" in milliwatts-seconds

Thesis Demonstration by Varistor Applications

To demonstrate our thesis by the ***ad absurdum*** process, we will compute the "energy in the surge" as defined by the trap-baiting definition of "specific energy" for three surge events such that all have the same "specific energy" but different voltage levels, waveforms, and durations. Then, making a further assumption for the unknown impedance of the surge source, we will compute the energy actually dissipated in the varistor for these different voltage levels, waveforms, and durations, and observe that the resulting deposited energy is not the same !

Elementary example: basic calculation with fixed impedance

As a first easy-to-follow step, we take three rectangular pulses, all selected to have the same "specific energy" but different voltage levels and corresponding durations, and compute the energy deposited in a nonlinear varistor having a given maximum limiting voltage, assuming that the source of the surge is a voltage source with some arbitrary, fixed impedance. It is noteworthy that ***some source impedance has to be presumed***, because the varistor clamping action rests on the voltage divider effect of the source impedance and the dynamic (variable) varistor impedance prevailing for the resulting current.

Start with an assumed surge measurement of 1000 V with duration of 50 µs. The "specific energy" of such a surge event, according to the proposed definition, is:

$$(1000\ \text{V})^2 \times 50\ \mu\text{s} / 50\ \Omega = 1\ \text{joule}.$$

Now consider a surge with a peak amplitude of 316 V (316 = 1000 / √10) and a duration of 500 µs (500 = 50 × 10). Its "specific energy" is:

$$(316\ \text{V})^2 \times 500\ \mu\text{s} / 50\ \Omega = 1\ \text{joule}.$$

To complete the bracketing range, consider a surge of 3160 V (3160 = 1000 × √10), and a duration of 5 µs (5 = 50/10). Its "specific energy" is:

$$(3160\ \text{V})^2 \times 5\ \mu\text{s} / 50\ \Omega = 1\ \text{joule}.$$

We now apply each of the three voltage surges to a 130-V rated varistor (200 V at 1 mA dc), assuming an arbitrary source impedance of $Z_S = 1\ \Omega$. One can compute the resulting current or, for this simple example, make a fast-converging manual iteration without the help of a computer, as follows:

(a) assume a current I, and look up the resulting voltage V_V on the varistor I-V characteristic;

(b) compute $[Z_S \times I]$;

(c) is $[Z_S \times I] + V_V = 1000$ V ?

(d) If yes, I is correct, the energy deposited in the varistor is

$I \times V_V \times \Delta t$

If no, go back to (a) with a converging assumption for I.

Table 2 shows the results from this manual iteration for the three surges defined above. It is quite apparent that the constant "specific energy" for the three surges does not result in the same energy deposition. The dynamic impedance (V_V/I) of the varistor is also shown, to illustrate the well-known theorem that the power dissipated in a resistive load reaches a maximum for matched source-load impedance. This theorem is yet another reason why a surge to be applied to a varistor cannot be characterized in the abstract: one needs to know the source impedance (real and imaginary components) as well, to assess the energy sharing between source and load.

Table 2

Energy Deposited in a Varistor by a Surge, as a Function of Surge Parameters, All Surges Having a 1 Joule "Specific Energy" for a Source Impedance of 1 Ohm

Rectangular Surge Parameters				Source/Varistor Response to Surge			
Postulated amplitude (V)	Postulated duration (µs)	"Specific energy" (J)	Varistor current (A)	Varistor voltage (V)	Varistor impedance (Ω)	Power in varistor (W)	Energy in varistor (J)
316	500	1	20	296	15	5920	2.96
1000	50	1	630	370	0.59	233 000	11.65
3160	5	1	2700	460	0.17	1242 000	6.21

Computer calculation with multiple combinations

We now compute the energy deposited in three varistors of three different maximum limiting voltages, for two combinations of voltage levels and durations that produce the same "specific energy," each with classical waveform (Ring Wave or Combination Wave), sized to produce 1 joule of energy dissipation in a 50-Ω resistor, according to the classical formula cited earlier, and for three values of source impedance. We can anticipate that the peaks will be quite different, foreboding very different effects on equipment. In fact, the peaks turned out to be 3 kV and 1.2 kV, respectively for the two waveforms.

Applying these two waveforms to a family of varistors typically used in 120-V or 240-V power systems, we computed the energy deposited in these varistors for three arbitrary source impedances (assumed to be ohmic), using the EMTP program[16] to input closed-form equations for the open-circuit surge voltage. The results are shown in Table 3. These simple illustrations show that even the concept of "specific energy" proposed as an improvement over the concept of "energy in the surge" cannot be used to select a candidate varistor energy-handling rating, and serves no useful purpose in characterizing the surge environment.

Table 3

Energy Deposited in Varistors by Ring Wave and Combination Wave "1 Joule Surges" For Different Source Amplitudes and Varistor Nominal Voltages

Surge parameters (All for 1 J)	Source impedance (Ω)	Varistor nominal voltage (V)	Peak current in varistor (A)	Energy deposited in varistor (J)
Ring Wave 100 kHz 0.5 µs rise time (3 kV peak)	1	130	2732	7.97
		150	2677	8.53
		275	2245	10.7
	12	130	239	0.55
		150	234	0.60
		275	208	0.81
	50	130	58	0.12
		150	57	0.13
		275	51	0.18
Combination Wave 1.2/50 µs (1.2 kV peak)	1	130	800	10.8
		150	739	10.7
		275	426	6.24
	12	130	72.1	0.87
		150	68.4	0.89
		275	45.0	0.64
	50	130	17.7	0.21
		150	17.1	0.21
		275	11.4	0.16

Conducting Future Surveys: Make Recordings That Make Sense!

Recording Relevant Parameters

In an effort to acknowledge the legitimate quest for the single number characterization, we should offer alternatives, not just stay with a negative vote The solution might be to tailor the surge characterization to the intended application, that is, take into consideration the failure mode of the specific equipment, and present the data in a form most suited for that equipment. Of course, this would mean not only avoiding a single number, but actually providing combinations of parameters, each combination best suited to a particular type of victim equipment, according to their failure modes.

The recently-approved IEEE Recommended Practice Std 1159 on Monitoring Power Quality[17] offers some guidance on conducting surveys, including not only surges, but other parameters. The Working Group that developed this standard has now established task forces to develop further recommendations on processing and interpreting the recorded data, including more uniform formats.

Table 1, discussed earlier, presented a matrix of surge parameters and types of equipment, showing for each type of victim which surge parameter is significant or insignificant. In compiling that table, the authors sought to identify all types of potential victims. As it turned out, the term $[v^2 \times dt]$ or its integral, alone, is not directly involved in the failure of any of the equipment listed in Table 1. A more complete set of data, associated with specific equipment sensitivity, will be needed to characterize the surge environment and achieve compatibility between that environment and equipment to be installed.

The fallacy of present-day voltage measurements

Another consideration that must be observed in conducting and reporting the monitoring of surges is the proliferation of SPDs in end-user installations. It is unlikely today to find an installation where some SPD is not present, either as a deliberate addition to the system, or as part of the connected equipment. Aware of this situation, some researchers have attempted to disconnect all known SPDs from the system being monitored so that results would represent the "unprotected location" situation such as that initially described in IEEE 587-1980[18], the forerunner of ANSI/IEEE C62.41-1991[19].

However, even this precaution of disconnecting all known SPDs does not guarantee that some undetected SPD might not have been left connected somewhere and thus invalidate the record. Thus, extreme caution must be applied to reporting and interpreting voltage monitoring campaigns conducted after 1980 [20].

We now propose a change in the protocol for the monitoring of power quality in ac power systems. This change has become necessary because end-user power systems are no longer what they were at the time the early surveys of transient overvoltages were conducted, a time at which measuring transient voltages did indeed make sense. Varistor-based surge-protective devices (SPDs) have become so ubiquitous in low-voltage ac power systems that hardly any location can be found where there is not some form of transient voltage limitation in effect. Attempting now to characterize the environment so that appropriate SPDs could then be prescribed for specific locations based on voltage measurements would be quite misleading. What such a measurement would yield today is no longer the surge characteristics of the monitored ***system***, as it was at the time of the early surveys, but the ***residual voltages*** of whatever SPDs are installed nearby.

Making meaningful measurements

The proposed change in monitoring practices is to insert a current transducer between the low-voltage power system being monitored and the existing monitoring instruments. This transducer would consist of an SPD with the minimum tolerable voltage rating across the power line, to be connected at some point of an installation, and serve as a "magnet" for attracting the impinging surges. To use a metaphor, this SPD in effect becomes the "winning bidder" by offering to the impinging surge the path with lowest clamping voltage among all the parallel-connected SPDs of the installation.

A current transformer with the "magnet SPD" in the primary and an appropriate burden on the secondary (Figure 2) would be used to feed the resulting voltage signal into the existing power quality monitoring instruments now used by many organizations and individual researchers. Typically, the voltage channels have higher frequency rsponse that current channels. In this manner, the surge current attracted by the "magnet SPD" can be recorded to find the true character of surge events at that particular location, despite the presence in the local system of any and many unknown and uncontrolled SPDs.

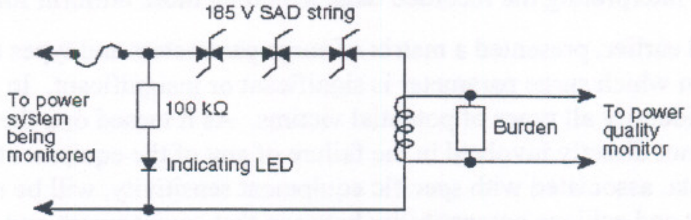

Figure 2 - Schematic of the transducer

The current transducer would consist of a string of silicon avalanche diodes (SADs) in series with the primary of a current transformer with a burden connected across its secondary, an overcurrent protective fuse in series with the diodes, and an indicating light to signal a blown fuse. Because the very principle requires that the SAD string have a clamping voltage lower than any other SPD in the installation, it would be the most vulnerable to a large swell. To remove the transducer from the system in case of failure of the SAD string, the fuse is provided ahead of the transducer circuits.

In the final design that would be used to deploy a number of these transducers, all of these components would be included in a package derived from the so-called "plug-in SPD" which are offered by many manufacturers. Using the external package of such a device will provide a low-cost envelope to build a few hundred transducers with no tooling costs and yet provide a package suitable for connection to wall receptacles in end-user systems.

It should be noted that only one channel of the monitor need to be allocated for recording the surge current. While the determination of power and energy deposited in the SAD requires knowledge of three parameters: current, voltage, and time, for the calibrated SAD built in the transducer, the voltage can readily be computed from the device I-V characteristic when the current waveform is known.

Preliminary results on the feasibility of such a recording system have been obtained: a suitable silicon avalanche diode has been identified and proven to act as a "magnet," even in the presence of "competing" metal-oxide varistors, and yet able to withstand the temporary overvoltages that can occur in the system. The current transformer can be any of readily available low-cost transformers; for the purposes of recording the surge events in the environment, the exacting accuracy of a laboratory-grade pulse current transformer would not be necessary.

The power system can include several branch circuits to supply the loads, some of which featuring SPDs incorporated into load equipment or installed by the end-user. At some point of this system, selected for convenience by the instrument operator, the transducer will be installed. A key point of the proposal is that pinning down the actual location of the monitor is no longer a concern because of the "magnet" effect of the low-clamping SAD string.

By design, the string of diodes is intended to become the "magnet" that will attract the impinging surges. We recognize that this winning bid can be ensured only within a certain radius from the transducer. Increasing distances between the transducer and competing SPDs eventually produces a decoupling of the two devices and might allow a competing SPD connected upstream from the transducer to divert the surge first. This situation is the reverse of that sought when making studies of the coordination of cascaded SPDs, where the concern is to ensure that a heavy-duty SPD located upstream of a lower-duty SPD is sufficiently decoupled so that an impinging surge will be diverted by the upstream SPD. The parameters of cascade coordination have been addressed at length in the literature [21] [22] [23] [24] and will not be discussed here. For typical circuit lengths in a low-voltage installation, our tests have demonstrated that the SAD string of Figure 2 offers a sufficiently low voltage path for impinging surges that it will indeed be the magnet.

More sophisticated analysis can be performed by applying the numerical modeling techniques developed in the referenced modeling studies [21-24], extending the distances and combinations of competing SPDs to determine how extensive an installation can be and still have the transducer remain the winning bidder. In this manner, the pitfall that threatens credibility of contemporary voltage recordings (uncertainty about other unknown SPDs connected in the system that can produce misleading results of low surge activity) will be eliminated.

Program Implementation

The next step in making the change from surge voltage recording to surge current recording would be to recruit enough participants willing to acquire the transducer and use their existing commercial monitor(s) to record the occurrences of surge currents attracted by the transducer. The transducer could be produced in cooperation with a manufacturer of a plug-in SPD, so that a readily adaptable outside package could contain the transducer components and provide a simple and safe way of connecting it to a receptacle.

Within the IEEE, a new Task Force of the Standards Coordinating Committee on Power Quality SCC22 is developing protocols for reporting monitoring results; hopefully, the concepts presented in this paper will be taken into consideration by that Task Force and by other organizations interested in making surveys for characterizing the electromagnetic environment. The IEC is also developing guidance documents on measurement methods in the area of power quality, where this shift of focus should be taken into consideration.

Conclusions

The attempt to characterize the surge environment by a single number -- the "energy in the surge" or "specific energy" -- is a misleading approach that should most definitely not be used in Power Quality research. There are at least four reasons for this prohibition:

1. The concept that energy can be defined in the abstract from a single measurement of voltage across the lines of an undefined power system is a faulty oversimplification.
2. The potential victims of a surge event have responses that reflect their design and for many, their failure modes can be totally independent of any energy consideration.
3. The prime interest of energy consideration is related to the energy-handling capability of metal-oxide varistors. The energy deposited in such a device by a given surge event depends on amplitude, waveform, source impedance, and varistor characteristics, and not on the "effective energy."
4. Last but not least, the proliferation of surge-protective devices (SPDs) in low-voltage, end-user facilities makes the recording of surge voltages a fallacy as the recorded voltages now represent the response of the installed (and generally unknown) SPDs in the installation, not the actual threat of impinging surges. That threat can now only be assessed by installing an instrument that will attract impinging surges to itself and measure the current that can be delivered by the surge.

Future surveys should be conducted keeping in mind the relevant parameters for characterization such as peak amplitude, maximum rate of rise, tail duration -- but not "energy." Relevant and realistic assessment of surge stress threats must consider not only all the characteristics of a surge event, but also the source of the surge and the failure mechanisms of potential victim equipment. Standards-writing bodies concerned with characterizing the electromagnetic environment in low-voltage power systems could make an important contribution by giving recognition to the new situation and shifting focus from surge voltage measurements to surge current measurements.

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