No Joules for Surges:
Relevant and Realistic Assessment of Surge Stress Threats

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

The 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. Examples are given of equipment for which a failure can be caused by a surge voltage, but with or without relationship to the energy involved in the process.

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. This subject was addressed in several other papers presented on both sides of the Atlantic (See in Part 5 "Keeping up"-1995; Make sense"-1996; Joules Yes-No-1997; "Novel transducer"-2000; and "Galore"-1999 in Part 2), in persistent but unsuccessful attempts to persuade manufacturers and users of power quality monitors, and standards-developing groups concerned with power quality measurements to address the fallacy of continuing to monitor surge voltages in post-1980 power distribution systems As it turned out, the response has been polite interest but no decisive action.

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Abstract : **The paper challenges attempts to characterize the surge environment in low-voltage end-users power systems by a single number -- the "energy in the surge" -- derived from a simple voltage measurement. Our thesis is that such attempts are neither realistic nor relevant. The paper shows 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 per se, but only to a well-defined combination of source and load. In particular, there is no meaningful relationship between the "energy" in a surge event and the energy actually deposited in a varistor by this surge event. 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.**

I. INTRODUCTION

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 conducted by organizations such as Bell Laboratories [1], Canadian Electrical Association [2], General Electric [3], IBM [4], National Power Laboratory [5] and other researchers, including Goedbloed [6], Hassler & Lagadec [7], Meissen [8], and Standler [9] have been limited to the measurements 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 and 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 now 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. Therefore, future surveys of surge events conducted with present monitoring instruments or with even better instruments will need to include more comprehensive -- and hopefully standardized methods of presenting and interpreting the results.

II. 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.

Our 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.

III. 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.

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These mechanisms 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.

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 related to energy.

3. Semiconductor devices, such as thyristors responding to the rate of voltage change can be turned on by a surge [10], 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 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, exemplified by the metal-oxide varistors that became so prevalent after their introduction in the mid-seventies, 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." (To be absolutely correct, the ultimate failure mode of a triac or a light bulb may be indirectly influenced by the energy dissipated in the device during the surge, but the root cause, the trigger, of the failure is not the energy.) Considering the explosive proliferation of varistors, however, one might find some extenuating circum-stances 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.

IV. 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 monitor 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 [11].

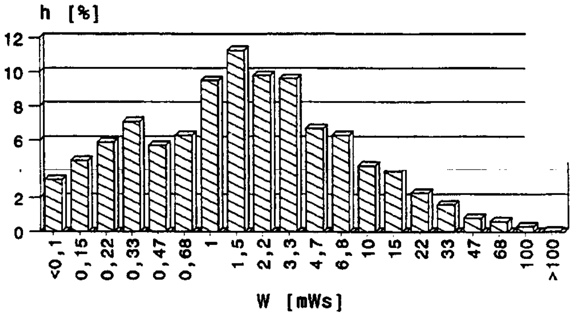

Figure 1 - Example of report of survey result [11] with number of occurrences as a function of "energy" in milliwatts-seconds

Acknowledging that indeed, the selection of an appropriate varistor should reflect the level of threat to which it will be exposed, 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.***

V. 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!

1. Elementary example: basic calculation, 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 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 amplitude of 316 V (1000 / √10) and duration of 500 µs (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 (1000 × √10), and a duration of 5 µs (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 $[Z_S \times I]$;

© 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 1 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.

2. Calculation with changing the surge source impedance

As the next step toward reality, we repeat the manual computations for different values of the impedance of the voltage source, still for the same "measured specific energy" and for the case of the 1000 V rectangular pulse. Somewhat arbitrarily, but no more arbitrary than the 50-Ω value used in the definition of "specific energy", we select three values of the source impedance.

Bear in mind that the reported measurements of surge voltages have never provided any information on the system source impedance to be associated with the reported surge. As a further oversimplification (an unjustified step in the real world), we will accept the assumption implied in the computation of the "specific energy" that this impedance has only real components, or is a characteristic impedance. Three values are used in the following examples.

TABLE 1

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)	Computed "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	1 242 000	6.21

- *50 Ω*, to go along with the proposed definition of "specific energy" (high-frequency measurements are often made in a 50-Ω environment and may be the reason for the value selected in the proposed definition).
- *2 Ω*, the so-called effective impedance of a Combination Wave generator, which is "deemed to represent the environment" as stated in the ANSI/IEEE Recommended Practice C62.41-1991 [12];
- *400 Ω*, a number sometimes cited as the characteristic impedance of an overhead line.

Again here, a simple manual iteration yields the result by postulating a varistor current, looking up the corresponding voltage on the I-V curve, such that this voltage is equal to the driving surge voltage, reduced by the voltage drop in the source for the postulated current. Table 2 shows the results for the three examples of assumed source impedance and a 130-V rated varistor.

3. Computer calculation with multiple combinations

We now compute the energy deposited in three varistors of three different maximum limiting voltages, for three combinations of voltage levels and durations that produce the same "specific energy," each with classical waveform (Ring Wave, Combination Wave, Long 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, 1.2 kV, and 220 V respectively for the three waveforms. Applying these three 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 [13] to input closed-form equations for the open-circuit surge voltage. With the 220-V level of the Long Wave, predictably the current in a 130-V rated varistor is very low and the resulting energy deposition is negligible. The results for the Ring Wave and Combination Wave are shown in Table 3. These simple illustrations show that the concept of "specific energy" cannot be used to select a candidate varistor energy-handling rating.

VI. HOW TO PROCEED IN FUTURE SURVEYS

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.

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 [14], the forerunner of ANSI/IEEE C62.41-1991 [12].

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.

The recently-approved IEEE Recommended Practice Std 1159 on Monitoring Power Quality [15] offers 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 4 presents a matrix of surge parameters and types of equipment, showing for each type of victim which surge parameter is significant or insignificant. The authors have sought to identify all types of potential victims (and invite additions to this list). Inspection of Table 4 reveals that the [$v^2 \times dt$] integral, alone, is not directly involved in the failure of any of the listed equipment.

TABLE 2

ENERGY DEPOSITED IN A VARISTOR BY A "1 JOULE SURGE" FOR THREE DIFFERENT VALUES OF SOURCE IMPEDANCE

Surge Parameters	Source/Varistor Response to Surge					
Rectangular, 1000 V - 50 µs ("Effective energy"is 1 J)	Source impedance (Ω)	Varistor current (A)	Varistor voltage (V)	Varistor impedance (Ω)	Power in varistor (W)	Energy in varistor (J)
	2	330	340	1	112 200	5.6
	50	14	300	21	4200	0.21
	400	1.8	280	156	504	0.025

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

TABLE 4

SIGNIFICANT SURGE PARAMETERS (X) IN THE EQUIPMENT FAILURE MODES

Type of equipment	Surge parameters					
	Source impedance	Peak amplitude	Maximum rate of 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 layer		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.

VII. 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 three 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.".

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."

Furthermore, a 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.

VIII. ACKNOWLEDGMENTS

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