Testing Varistors against the VDE 0160 Standard

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Significance:
Part 2 – Development of standard – Reality checks

Demonstration ad absurdum:
Accepting the premise of prevalent 100/1300 high-energy surges and subjecting typical metal-oxide varistors to the stress from a test performed with a prototype generator leads to the conclusion that most of the billions of varistors in service should fail at alarming rates – but we know they do not. Ergo, the premise is not valid.

This paper was part of a successful effort to discourage the IEC TC77 from including that 100/1300 test in the regimen of across-the board EMC testing.

(See also paper “Validating Surge Tests ..." in this Part 2 for a demonstration by numerical modeling.)

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Abstract *— High-energy surge tests have been performed on metal-oxide varistors of a type in common use, according to a proposed IEC standard derived from German Standard VDE 0160. The surge generator used for the test was a prototype commercial device developed especially to deliver the 100/1300 μs waveform specified by VDE Standard 0160. Depending on the position of the varistor within its manufacturing tolerance band, failure or degradation can occur, validating the concern that this test requirement may be too severe for universal application.*

INTRODUCTION

Concerns over the occurrence of high-energy surges associated with current-limiting fuse operation (Meissen, 1983 [1]) have led the German standards organization (VDE) to specify a high-energy surge test to be applied to electronic equipment installed in industrial environments (VDE 0160, 1988 [2]). Essentially, the test requires discharging into the ac line interface of the equipment under test (EUT) a capacitor of such capacity that the specified waveform is generated, initially charged at a voltage suitable for producing a peak of 2.3 times the power-system sine-wave peak (Figure 1). Technical Committee 77 of the IEC has included this test in its menu of surge immunity tests (TC77B/WG3, 1990 [3]), without limiting the scope of application to industrial environments intended by the Meissen paper. Thus, this test is likely to become a general requirement imposed on commercial and consumer equipment, unless its implications are recognized. In the absence of a readily available surge generator, computer modeling of the test had previously been performed (Fenimore & Martzloff, 1990 [4], 1991 [5]). The findings of these simulations have shown that typical varistors, of which many millions have been installed and continue to operate satisfactorily, cannot survive the proposed IEC/VDE test because excessive energy would be deposited in these varistors during the surge. The recent availability of a prototype surge generator made it possible to subject typical varistors to the VDE/IEC surge, as reported in this paper.

TESTING VARISTORS WITH HIGH-ENERGY SURGES

Schaffner*, a manufacturer of surge generators, has now developed a prototype that can produce the VDE 0160 surge; in response to an invitation to try out this prototype, an informal work session was conducted at the Schaffner facility to subject typical varistors to the VDE 0160 surge. The generator includes the specified capacitor, up to 6000 μF, the necessary dc supply to charge the capacitor, a 220-V ac supply (for European environments), and suitable means to decouple the test specimen circuit from the laboratory ac system. Details of the circuits are still proprietary, and only the output of the generator is described in this paper. A chronological recitation of the work session would require first a discussion of the various considerations and conditions of the test. Recognizing the natural curiosity of the readers, let it be stated here that one varistor was destroyed during the test, and the other (barely) survived, consistent with the predictions of the computer modeling. Having thus given away the outcome, let us now proceed with the detailed recitation of these considerations and conditions.

** As a policy, the National Institute of Standards and Technology disclaims any implied endorsement of a commercial product when identifying such products for the sole purpose of adequately describing the equipment used in the experiment. In this particular case, the prototype generator used in the tests was the only one known to be available. Furthermore, there is no certainty that Schaffner will offer a commercial product based on this prototype.*

Voltage across the test specimen and current delivered by the surge generator were recorded with the instrumentation available at the Schaffner engineering demonstration facility. The software package included in the digital storage oscilloscope did not have the capability of computing the power ($i \times v$) dissipated in the varistor and integrating it into total energy deposited. Manual integration of the recorded traces was performed after the tests. This computation yields results of sufficient magnitude (that is, large overstress of the varistor) to make precise computing unnecessary in evaluating the outcome of the test.

The test specimens (EUT) were 20-mm diameter varistors, consisting of two 130-V rms rated devices connected in series, a good approximation of the practice of applying 250-V rated varistors in the 220-V equipment used in Europe (Martzloff and Leedy, 1989 [6]). The nominal voltage, V_{nom}, of each varistor (voltage measured with 0.5 mA or 1 mA dc injected in the varistor) was determined before the test for each device. One varistor pair (referred to as EUT #1) had a nominal voltage of 392.6 V, the other pair (EUT #2), 399.5 V. The nominal voltage for a 250-V rms varistor is 390 V, the minimum 354 V, and the maximum 429 V (Harris Manual, 1990 [7]). Thus, EUT #1 is situated at 1% above the nominal value of a 250-V rated varistor, while EUT #2 is at 2.5% above the nominal value.

To test the varistors under the worst case condition (that is, the varistor at 10% below nominal, thus drawing energy from the generator for a longer portion of the surge waveform), the test voltage should be raised above the voltage specified for nominal test conditions. To place the varistor under conditions equivalent to those prevailing for a -10% specimen, a varistor at some tolerance level must be subjected to the same current as that occurring for a -10% varistor at the nominal test voltage. With the nominal VDE 0160 test voltage of 2.3 times the 220-V peak (714 V), the available EUT varistor specimen can be tested in a manner equivalent to a -10% tolerance varistor by raising the test voltage.

For EUT #1 which is 1% above the V_{nom} of a 250-V rated varistor, the test voltage should be 10% higher than the nominal 714-V peak, plus 1%, that is, 792 V. For EUT #2, 2.5% above the V_{nom}, the test voltage should be 12.5% higher, 803 V. This increased test voltage will place the varistor at the correct value of current on its I-V characteristic, but raises the power dissipated in the varistor by the same percentage. Thus, the energy deposition in varistors other than -10% tested under the artificially raised test voltage received 11% or 12.5% more energy than what a varistor at -10% would have received. However, considering the energy levels observed in the tests reported below (about 200% of rated levels, this 11-12.5% excess does not affect the conclusions. The significant parameter to be observed is the current level, and that correct level was indeed achieved by raising the test voltage.

The VDE 0160 document states that the *specified surge test voltage should be maintained* across the terminals of the EUT, rather than the usual method of having a preset open-circuit voltage, and then connect the EUT *without changing the generator setting* (the so-called 'let-it-rip' mode [5], and (ANSI/IEEE C62.41-1987, [8]). Meissen confirmed this interpretation of the document [9], so that the charging voltage of the generator capacitor was increased toward obtaining the specified voltage with the EUT connected, using an expendable EUT varistor during preliminary tests. However, the prototype generator output voltage, with maximum charging voltage and with varistor connected, could only be raised to 774 volts (Figure 2) instead of the 792 V or 803 V necessary to place the #1 and #2 varistors in the -10% tolerance situation. Thus, EUT #1 was actually tested in a condition corresponding to 774/792 = 98% of the worst case level, and EUT #2 at 774/803 = 96% of the worst case level. In other words, EUT #1 was tested as if it were at a -8% tolerance level, and EUT #2 at a -6% tolerance level with respect to a 0% tolerance on their V_{nom}.

The manufacturer's specifications [7] show a 70-J single-pulse energy rating for the 130-V varistor, or 140 J for two in series. Figure 3, from Ref [5], shows the predicted energy deposition as a function of the varistor position in its tolerance band, for the test condition where the voltage is maintained across the EUT by readjusting the surge generator charging voltage.

The VDE 0160 document shows an elementary circuit diagram (Figure 4) with a maximum of 5 m of leads between the input port of the test specimen and the point of injection of the surge. Accordingly, the test circuit set up by Schaffner included approximately 5 m of leads "suitable for a 16 A load" between the varistor and the output of the generator. Thus, the impedance presented by the test specimen to the applied VDE 0160 surge includes a resistance that will reduce the stress of the varistor; however, this reduction is not readily recognized by the simple mention in the figure of a 5-m maximum lead length, and the cross-section of the conductors is not specified. Operators can interpret the test procedure in a way producing maximum stress (a short lead of large cross section) or a minimum stress (maximum of 5 m of leads with small cross section).

In accordance with the interpretation of the Figure 4 diagram, the voltage measured and shown in Figure 2 is the total of the voltage developed across the varistor and the lead drop. To evaluate the implications of this interpretation, the next test was performed, without changing the generator setting (at its maximum available voltage), with the voltage measurement made at the varistor terminals (Figure 5). Note the 700-V peak in this test, or a 74-V difference (10%) from the value recorded in Figure 2. In the modeling of References [4] and [5], the effect of this 5-m test lead had not been included, so that the conclusions of the modeling are more pessimistic than the consequences of a test condition with a lead length included. Thus, the varistor would be under 10% less voltage stress (keep in mind the nonlinear relationship between voltage and current) than the model prediction, and possibly could survive.

THE DEATH OF A VARISTOR

According to a subsequent amendment to the VDE 0160 test specification, the maximum* capacitor value and the duration of the surges may be reduced to 300 μs for equipment installed in circuits protected by fuses of less than 35 A continuous rating. This reduction will provide significant relief to varistors included in non-industrial environments. However, the IEC document [3] does not include that reduction. The test sequence for EUT #1 included two surges with this reduced stress (Figure 6), followed by surges with the full 6000 μF capacitance and full 1300 μs duration, at the maximum available generator voltage, as shown in Figure 2. Before and after each surge, the varistor V_{nom} was recorded to track any shift in characteristics, comparing it to the maximum shift of 10% allowed in the manufacturer's specifications.

The test sequence and results for EUT #1 (a specimen in the -8% tolerance position), starting with no prior surges applied, were the following:

Shot 1:	718 V crest, 400 μs duration, V_{nom} shift of 1% (Figure 6)
Shot 2:	768 V crest, 1100 μs duration, V_{nom} shift of 1%
Shot 3:	774 V crest, 1400 μs duration, V_{nom} shift of 1% (Figure 2)
Shot 4:	Repeat, same settings as shot 3 (voltage measured at varistor, Figure 5), Varistor (a) of pair punctured Varistor (b) of pair externally intact, but V_{nom} = 0 (short circuit) Energy deposited in the varistor; approximately 300 J (215% of rating)

The same test sequence was then applied to EUT #2, that is, first two shots at reduced stress, and then full stress for shot 3 and four additional shots. The V_{nom} shift grew from 1% after the first shot to 6% after the last shot, as measured after cooling down following the test. By the time the author had returned to the United States (20 days later), the shift in V_{nom}, determined by more systematic measurement at NIST, was reduced to 4%. The difference between the 6% immediately after the test and the 4% after 20 days may be the effect of a slow recovery of the material, or a difference in the precision of the measurements, or both.

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* *The surge duration is the specified parameter in the VDE 0160 document, therefore the required value of the capacitor is dependent upon the impedance of the EUT.*

Notwithstanding the shift in V_{nom}, no apparent external damage was visible, except for some darkening of the red epoxy coating. Thus, while EUT #2 did survive a test corresponding to a -6% tolerance position, the onset of permanent change leading to failure was observed.

DISCUSSION OF THE RESULTS

From the simulation predictions, it was expected that the varistors would be destroyed by the test, even though the (late) realization of the stress reduction provided by the lead length does somewhat change the situation. In other words, the 10% loss of voltage caused by the leads places the varistors used in these tests at respectively +2% and +4% in the tolerance band, a condition that the prediction describes as marginal survival. The joule rating specified by the manufacturer tends to be conservative, so that it may take more than 140 J to destroy a varistor. Furthermore, a larger population of test specimens may produce a distribution of more failure as well as more survivals as only two test points can only provide an indication, not a certainty. However, the conclusion is clear, that varistors of common use in commercial and consumer equipment would be in severe jeopardy if the full 100/1300 μs surge were applied, even with the mitigating effect of the 5-m lead length. Discussing the test results with Meissen, we agreed on the following conclusions:

1. There is no disagreement that the basic phenomenon of fuse blowing can lead to the high-energy surges described by Meissen in the heavy industrial environment (circuits with fuses above 35 A).

2. The prediction of varistor failure through modeling is consistent with the tests; the mitigating effect of the allowable EUT lead reduces the forecast of widespread failures, but varistors in the lower tolerance bands are still at risk.

3. The amendments to VDE 0160 providing for reduced maximum capacitance values (see the footnote on page 3) and reduced duration make the test more realistic. Further evaluation of these reduced stress levels would show appropriate limits of application.

4. However, this stress reduction has not yet been acknowledged by the IEC proposals (Figure 1, showing only one value of 1.3 ms is excerpted from the IEC document, not the amended VDE 0160 where the alternate duration of 0.3 ms is shown). This paper is therefore submitted to the engineering community at large as a recommendation of limiting the full duration of a 1300 μs surge and its high energy to the industrial environment for which it was first proposed.

5. The concept of readjusting the surge generator charging voltage to maintain a specified *test voltage* across the specimen is different from the usual practice of maintaining a fixed open-circuit voltage for the generator. However, it may be compared to the practice of readjusting the surge generator used for surge arrester tests at a specified *test current* level. As long as the implications of the procedure are recognized, either method may be suitable, if uniformly interpreted.

6. In its present form, the VDE 0160 document leaves open the possibility of different interpretations by different operators. Should the principle of a high-energy test be adopted by the IEC, more detailed specifications need to be developed and agreed upon by interested parties.

ACKNOWLEDGEMENTS

This successful work session was made possible through the cooperation of T. Hilger and M. Ryser of Schaffner. W. Meissen made the long journey from Erlangen, Germany to Luterbach, Switzerland to participate in the test, and reviewed the manuscript of this paper. The simulation predictions of References [4] and [5] were developed by C. Fenimore. All these contributions toward a better understanding of the VDE 0160 test implications are gratefully acknowledged.

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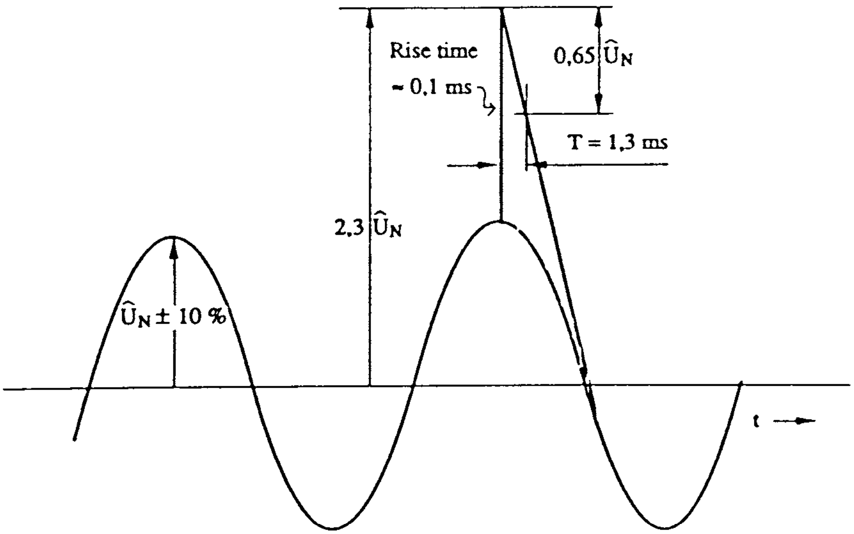

Figure 1. High-energy waveform specification (From Ref. [3])

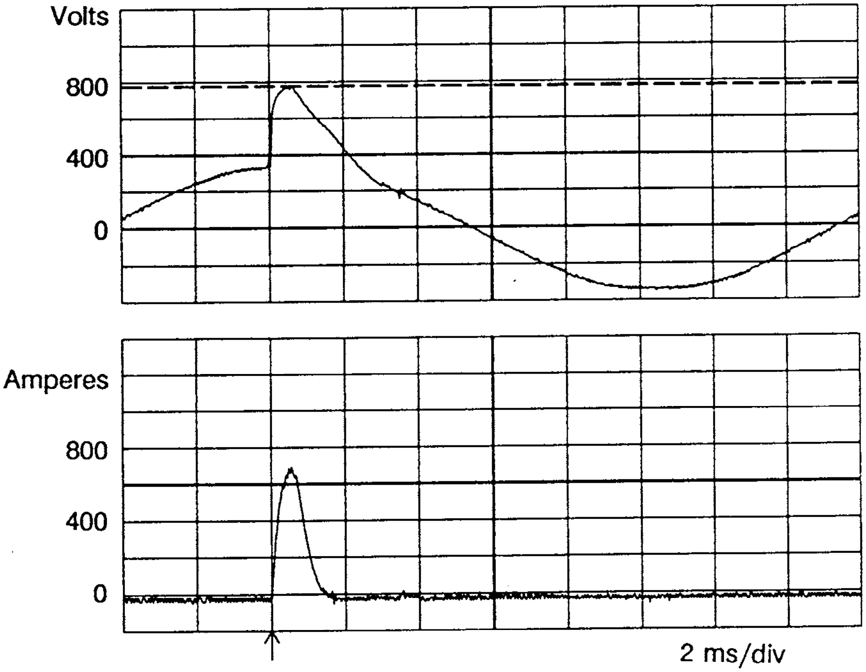

Figure 2. Voltage across and current through EUT #1

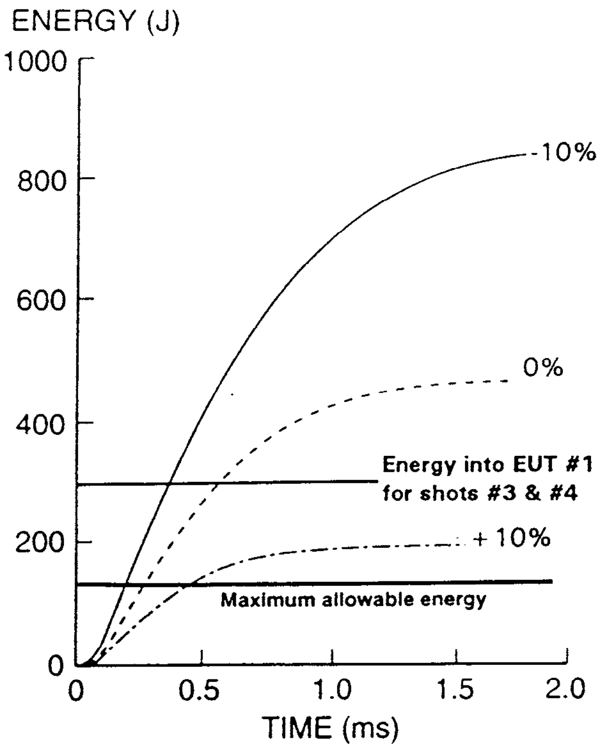

Figure 3.
Energy deposited in varistor as a function of tolerance of device compared to nominal value (From Ref. [5])

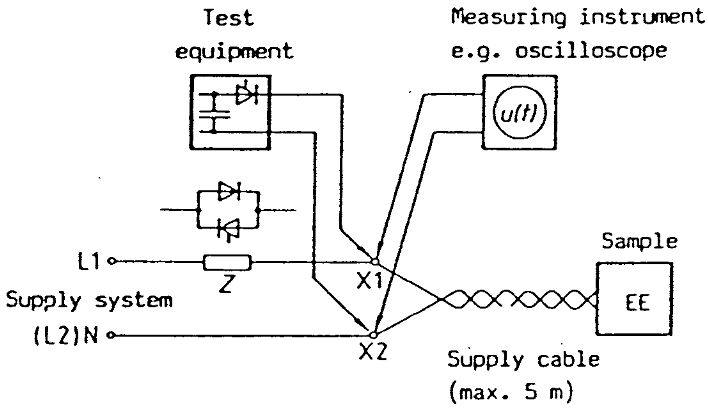

Figure 4. Elementary test circuit diagram (From Ref. [2])

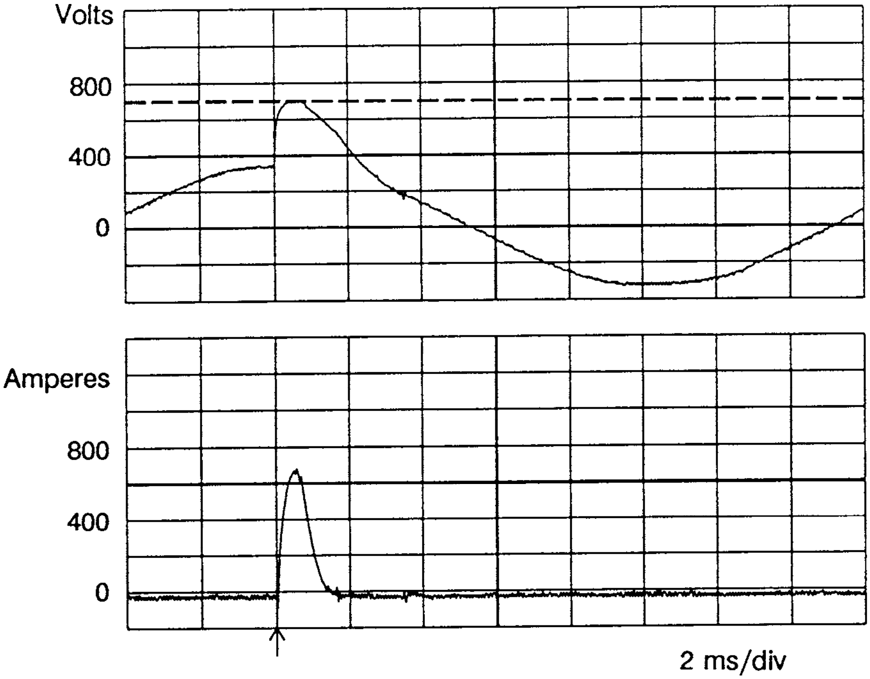

Figure 5. Voltage across and current through varistor only

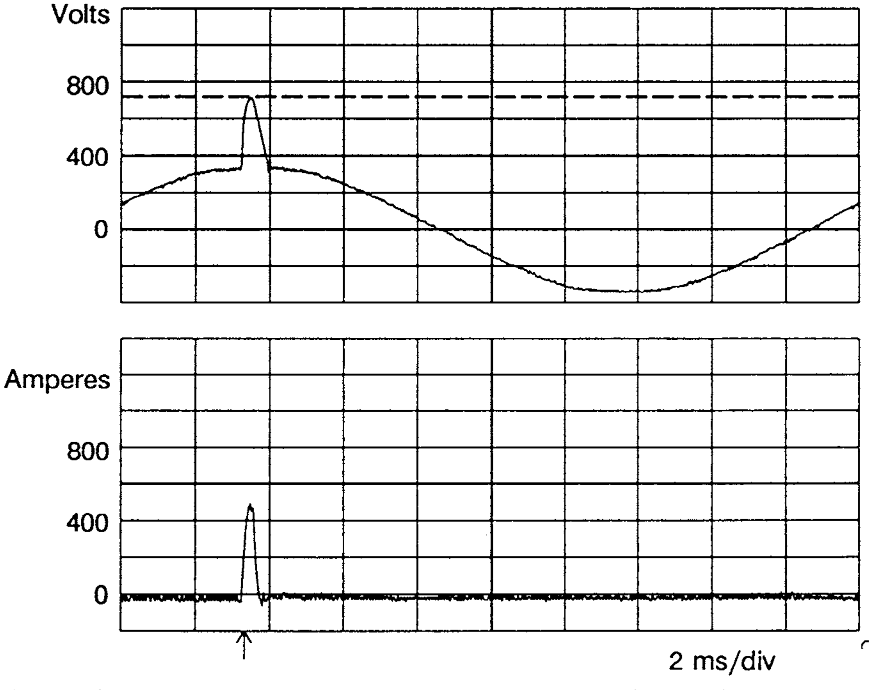

Figure 6. Voltage across and current through varistor with reduced stress