Incompatibility Between the 100/1300 Surge Test and Varistor Failure Rates

Charles Fenimore and **François Martzloff**
National Institute of Standards and Technology
Gaithersburg MD 20899 USA
f.martzloff@ieee.org

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Significance:
Part 2 – Development of standards – Reality checks

Demonstration ad absurdum:
Accepting the premise of prevalent 100/1300 high-energy surges and modeling the response of typical metal-oxide varistors 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 “MOV - VDE" in this Part 2 for an experimental demonstration.)

INCOMPATIBILITY BETWEEN THE 100/1300 SURGE TEST AND VARISTOR FAILURE RATES

Charles Fenimore and François D. Martzloff
National Institute of Standards and Technology
Gaithersburg, MD USA

Abstract – A proposed high-energy surge test featuring a 100/1300 μs waveform and a peak voltage of 2.3 times the peak voltage of the low-frequency mains is under consideration by the IEC. The energy storage capacitor suggested for the surge generator, originally specified as high as 25 000 μF, has been scaled down but is still at a level of several thousand microfarads. To determine the energy dissipated in various surge tests, numerical integratation is applied to a simple but realistic mathematical model of a test circuit. The energy that would be deposited into a varistor of the voltage rating commonly used in protecting load equipment, if subjected to this test, far exceeds the capability of the varistor, but reported varistor failure rates do not reflect such a situation. Thus, a re-examination of the premises that led to the 100/1300 μs test specifications appears necessary.

INTRODUCTION

The IEC Technical Committee TC77 is considering a surge test requirement based on the scenario of current-limiting fuses clearing a fault at the end of a cable, where the energy trapped in the system inductance causes a large transient at the time the fuse interrupts the current [1]. That scenario was first described and quantified by Meissen [2], and incorporated in German Standard VDE 0160 [3]. However, there seems to be an inconsistency between the predictable failure of varistors that would be subjected to this test, and the reported failure rate of varistors, considering that several hundred million of these varistors are currently connected across the mains in a wide variety of load equipment.

Accepting the premises that led to the specification of this test, the authors developed a simple circuit model that produces the specified waveform, with an energy storage capacitor having the value specified in the current amendment to VDE 0160 [4]. Applying the surge available at the output of the circuit model to varistors of the ratings commonly used in load equipment results in an amount of energy deposited in the varistor that exceeds by far the capability of the varistor.

If the scenario of fault-clearing by fuses occurs at a frequency such that a universal test should be required to simulate its effect on all equipment, then one would expect a substantial failure rate among the varistors incorporated in equipment in actual service. This expectation follows from the computations which show that typical varistors used in mains-connected equipment cannot survive such a test. While equipment failure rates are not widely published, anecdotal information and the sharing of field experience in the engineering community do not support the existence of a large failure rate attributable to that scenario. Therefore, the authors suggest that the premises that led to the specification of the test, the consequences of the test on in-service varistors, and the actual failure rates of these varistors should be examined to resolve the apparent inconsistency.

THREE FORMS OF THE 100/1300 TEST SPECIFICATION AND VARISTOR RATINGS

Figure 1 shows the parameters of the 100/1300 μs surge described in Ref [1]. The voltage level is specified as $2.3 \times U_{pk}$, the peak of the mains voltage. However, under the clause addressing the test generator specification, one finds the interim statement 'Under Consideration'. The VDE 0160 documents do not include specifications for the test circuit, but leave the circuit design to private industry [5]. Referring to working documents and the original and later amendments of VDE 0160, the test circuit essentially consists of an energy storage capacitor up to 25 000 μF discharged into the equipment under test.

A subsequent VDE amendment shows a table of capacitance values ranging from 700 μF for 660 V rms mains to 6000 μF for 220 V rms mains. According to the amendement, the capacitor charging voltage may be set at one of two levels, respectively 2.3× and $2 \times U_{pk}$, the peak of the mains voltage. Furthermore, two durations are also stated, the original 1300 μs and one reduced to 400 μs.

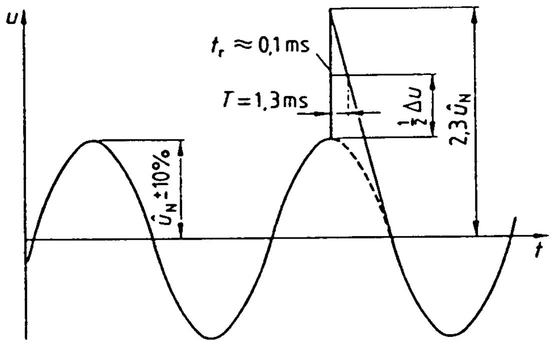

Figure 1. Parameters of the $100/1300\mu s$ surge test waveform from VDE 0160 [3].

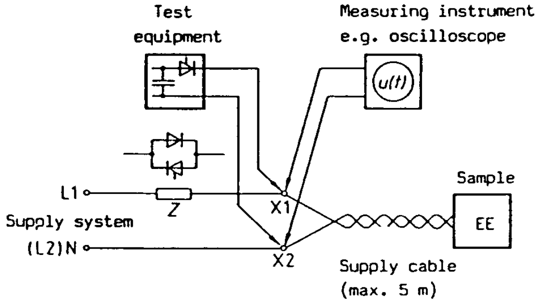

Figure 2. Schematic test circuit for the $100/1300\mu s$ surge test waveform from VDE 0160 [3].

For the sake of exploring the implications, the authors accept the $100/1300\,\mu s$ at $2.3 \times U_{pk}$ proposal and will develop conclusions on varistor performance under this proposed test, the more severe of the two levels and two durations. However, an ambiguity exists on the test procedure. Two different interpretations of the VDE 0160 text can lead to different test procedures: providing a fixed charging voltage for the energy storage capacitor or re-adjusting the voltage after connecting the test specimen.

These two different interpretations result in two approaches with two sets of different values for the model parameters. A first method, based on using fixed charging voltage, is the approach generally used in surge testing [6], [7], often described as "let it rip." However, the VDE 0160 standard contains a sentence that reads: "The test apparatus is used to generate the test voltage impulse between the terminals of the test specimen while it is operating." This statement would suggest a second method, that is, adjust the charging voltage with the test specimen connected. The implications of the two interpretations will be shown below.

A further statement reads "... under certain conditions, the required half-peak duration of the pulse of 1.3 ms cannot then be reached. In this case it shall be ensured that not less than 80% of the energy stored in the test device is supplied to the sample." A simple capacitor discharge circuit, as implied by Figure 14 of VDE 0160, reproduced here as Figure 2, will require a parallel resistance to pull the voltage of the 6000 μF capacitor down to half-value in 1.3 ms. The surge generator shown as "Test Equipment" in Figure 2 does not explicitly include such a resistance. Such a resistor will drain enough energy from the capacitor that it is not clear how 80% of the capacitor energy will be left for the sample. Thus, the computations presented here include three approaches:

1. Fixed initial charging voltage ("let it rip")
2. Fixed peak surge voltage (readjust initial voltage)
3. Expend 80% of the capacitor energy into the test specimen.

Metal-oxide varistors offered by manufacturers include ratings of 130 V rms for applications in 120 V systems and 250 V rms for application in 220 V systems. The motivation for using these varistor ratings in electronic equipment is, of course, the desire to provide the lowest possible clamping voltage to protect sensitive equipment [8]. Therefore, the model developed in this paper is applied to a 220 V system and a 250 V varistor. For these values, the peak surge voltage is $220 \times 1.41 \times 2.3 = 715$ V, and the varistor voltage (at 1 A) is 485 V.

ENERGY DEPOSITION IN VARISTORS FOR THREE TEST CRITERIA

A simple, but realistic model of a capacitor discharge through a wave-shaping circuit can produce the specified surge rise and duration of 100/1300 μs. Referring to Figure 1, this $1300\mu s$ half-maximum is that of the surge, which is superimposed on the mains sine wave. Thus, the surge duration of 1300 μs corresponds to the level of $U_{pk} + \frac{1}{2}(1.3 \times U_{pk})$, that is $1.65 \times U_{pk}$.

Figure 3 shows a simple test circuit which is the basis for the mathematical model. Without the metal oxide varistor (MOV) in place, the circuit is configured for the open-circuit discharge test of a model test generator. Using circuit component values of $C = 6000\,\mu$F, $L = 25\,\mu$H, and $R_s = R_p = 0.27\,\Omega$, the open-circuit voltage response is generated numerically and is shown in Figure 4.

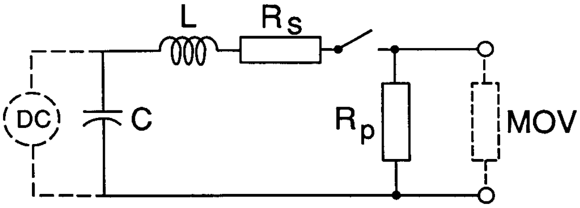

Figure 3. Schematic test circuit for the $100/1300\mu s$ surge test waveform used for the mathematical model. (The open-circuit test is performed without the MOV.)

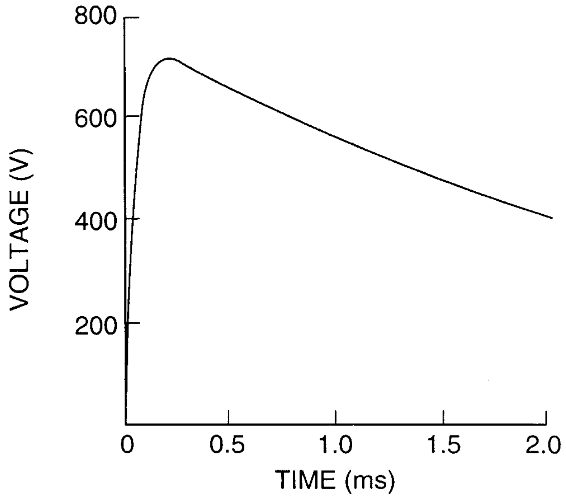

Figure 4. Plot of the open circuit voltage waveform obtained by discharging the capacitor in Figure 3 without the varistor in place.

The basic model is then modified by placing the varistor across the open-circuit terminals of the circuit in Figure 3. The non-linear I-V character of the MOV is expressed by the 'equation of state':

$$v_m = \lambda \left(\frac{i_m}{i_1}\right)^{1/p} + R_m i_m \tag{1}$$

in which i_m is the current through and v_m is the voltage across the MOV. This equation is a two-term reduction of the full five-term model for a varistor [9]. It is appropriate to the slow waveforms in this surge testing environment. The unit current, i_1, should be chosen to be characteristic of the problem. In the present application, $i_1 = 1\,\mathrm{A}$. Where doing so causes no ambiguity, we have suppressed the current unit, i_1, in the analysis. R_m is the series resistance of the MOV, in the examples used here, $0.12\,\Omega$. The voltage threshold for the MOV, λ, has a nominal value of 485 V. The exponent, p, is nondimensional and in the present calculation has been given the typical value of 31 [9].

The circuit model is formulated to produce a system of differential equations which are solved for q, the stored charge on the capacitor, i_m, and e_m, the energy deposited in the varistor. The voltage drops around the circuit must satisfy

$$v_L + v_{R_s} + v_m + v_C = 0 \tag{2}$$

which yields

$$L\frac{di}{dt} + R_s i + v_m + \frac{q}{C} = 0 \tag{3}$$

It is possible to express (2) as a differential equation in i_m because v_m is a function of i_m and Kirchoff's Law implies that i is a function of i_m, $i = i_m + v_m/R_p$. The evolution equations for q, i_m, and e_m are thus:

$$\frac{dq}{dt} = -i \tag{4}$$

$$\left[L\frac{di}{di_m}\right]\frac{di_m}{dt} = -R_s i - v_m - \frac{q}{C} \tag{5}$$

$$\frac{de_m}{dt} = i_m v_m, \tag{6}$$

where

$$\frac{di}{di_m} = 1 + \frac{R_m}{R_p} + \frac{\lambda}{pR_p} {i_m}^{1/p-1}. \tag{7}$$

The non-linear system (4-5) is equivalent to a second order equation for i_m. The initial conditions for i_m and e_m are zero, while $q(0)$ is chosen to generate the maximum voltage required by the test as specified below. The solution of the system is computed using a general purpose ordinary differential equation solver, PLOD, which permits a variable time-step size and handles stiff systems (those with widely differing time constants) [10].

1. Results with fixed initial charging voltage

Figure 5 shows the voltage, v_m, and current, i_m, waveforms at the varistor under the 'let-it-rip'mode, a procedure under which the open-circuit voltage of the generator is preset and no adjustment is made after connecting the test specimen. The desired waveform is generated with $q(0) = 9\,\mathrm{C}$. Note that the additional path in the circuit with the varistor in place reduces the peak voltage below that for the open-circuit test, from 715 V to 680 V. Figure 6 displays the time-resolved deposition of energy in the varistor, and compares it to the allowable energy deposition.

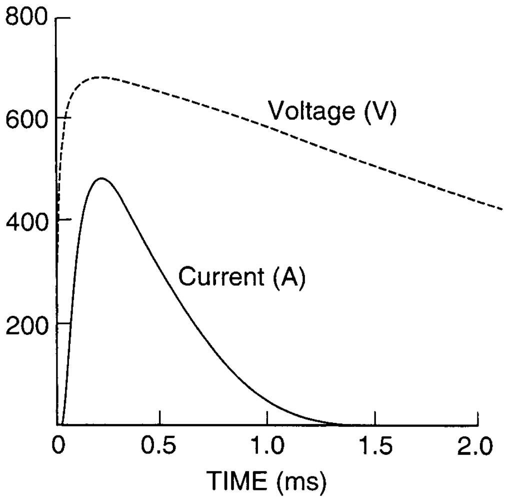

Figure 5. Plot of the current and voltage waveforms at the varistor with charge $q(0) = 9\,\mathrm{C}$ and with $\lambda = 485\mathrm{V}$.

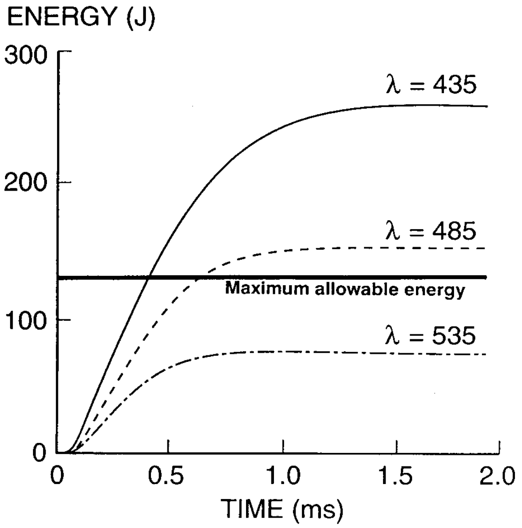

Figure 6. Energy waveforms at a fixed charge, $q(0) = 9\text{C}$, for dissipation in the MOV at three ratings of the varistor, $\lambda = 435\text{V}$, 485V, and 535V.

The three energy curves correspond to three values of the parameter λ, the voltage rating of the MOV. The values are $\lambda = 435$ V, 485 V, 535 V, which are the lowest, mid, and highest values for acceptable ratings from the manufacturer (a ±10% band about the nominal value of a varistor rated at 250 V). The typical energy rating for a 20-mm, 250-V varistor is 130 joules. Denoting by $e_m(t, \lambda)$ the energy as a function of time and of voltage rating, the total amount of energy deposited by the pulses, $e_m(\infty, \lambda)$, is displayed in Table 1. Only the highest voltage rating survives. This fundamental model suggests a gross inconsistency between the failure rate that the test would produce and the available information on actual failures of in-service varistors. The Appendix confirms these conclusions based on an analytical, inductance-free model for the test circuit.

TABLE 1
Energy deposited in a 20-mm dia, 250-V MOV as a function of tolerance on voltage rating, at fixed initial voltage ("let it rip")

Voltage tolerance (%)	-10	0	+10
Varistor voltage λ (V)	435	485	535
Energy e_m (∞, λ) (J)	257	152	74
Peak v_m (V)	615	645	673

2. Results with readjusted charging voltage

The authors note that VDE-0160 is not unambiguous on the character of the test procedure. The standard may be construed to require that the voltage maximum with the MOV in the circuit remain 2.3 × U_{pk}, rather than accept whatever value will occur under the 'let-it-rip' mode. Under this interpretation, the charging voltage of the generator must be increased to obtain the required level; additional energy is stored in the capacitor and destruction of the MOV is assured at all permissible tolerances, Figure 7. Thus, for the three values of the voltage tolerances given above the initial charges on the capacitor, $q(t, \lambda)$ to reach the voltage maximum, 715 V, and the energy deposited are displayed in Table 2. In each case, the energy rating of the MOV, 130 J, is exceded substantially.

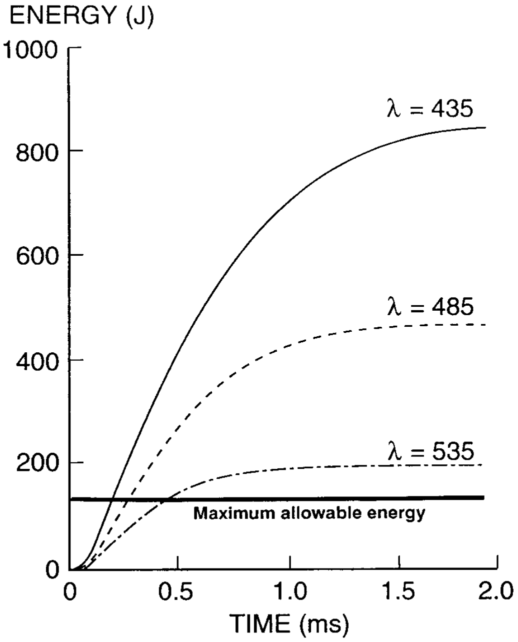

Figure 7. Energy waveforms with the peak voltage fixed, V_{max} =715V. The energy dissipated in the MOV is shown at three ratings of the varistor, $\lambda = 435\text{V}$, 485V, and 535V.

TABLE 2
Energy deposited in a 20-mm dia, 250-V MOV as a function of tolerance on voltage rating, at fixed (readjusted) peak voltage

Voltage tolerance (%)	-10	0	+10
Varistor voltage λ (V)	435	485	535
Energy e_m (∞, λ) (J)	839	459	192
Initial charge $q(0)$ (C)	11	10.75	10

3. Expend 80% of capacitor energy in specimen

An alternate criterion suggested by VDE 0160 is that 80% of the capacitor energy be dissipated in the MOV. For the simple circuit on which the present model is based, a ready calculation using the capacitively stored energy, $q^2/2C$ (of order 5000 J), shows that no more than 10% of the stored energy is spent in the MOV in the simulations according to the two approaches discussed above. Yet, these two tests are already destructive of the device. It seems likely that a test that would meet the 80% criterion would provide an even more severe stress to the equipment, and provide a greater disparity between the model results and field experience.

Thus, the authors suggest that a reexamination of the premises that led to the VDE 0160 Standard should be considered before incorporating a blanket requirement for such a test into new IEC surge immunity standards. The authors plan to perform actual tests on typical varistors to further support the computations presented in this paper.

CONCLUSIONS

1. A mathematical and derived computational model has been presented which permits the evaluation of many aspects of varistor performance over a range of conditions which are characteristic of the actual operating environment and also of the test environment contemplated by VDE 0160 and other surge standards.

2. Computer model predictions of the impact of the proposed 100/1300 μs surge test on the millions of varistors in service shows that these varistors should experience a greater failure rate than indicated by available information on actual failures. The simplified inductance-free model provides analytical confirmation of this result. This inconsistency raises serious questions on the proposed requirement of such a severe test to a wide range of equipment.

3. The lingering ambiguity on setting a constant open-circuit voltage or adjusting the voltage while the specimen is connected needs to be clarified. A constant open-circuit voltage is the generally accepted practice in surge testing. The premises that led to this new surge test may justify adjusting the charging voltage after the test specimen has been connected to the surge generator; that adjustment, however, results in larger amounts of energy being dissipated in surge protective devices, making the apparent incompatibility identified above even greater.

4. The criterion that 80% of the capacitive energy must be transferred to the test specimen may be difficult to satisfy and needs clarification. The authors have been unable to identify a simple circuit which satisfies the criterion while maintaining the required rate of decay under open circuit conditions.

5. While the authors do not question the validity of the fuse-blowing scenario, they recommend a critical review of the statistics of the occurrence of fuse blowing, of the use of varistors with low clamping voltage, and of the distribution of actual clamping voltage within manufacturing tolerances. The sensitivity model developed in this paper may be a useful tool in evaluating the effect of these tolerances. The authors also urge all users to share information on the observed failure rates, as well as to perform validating tests, in order to provide a broader perspective on these issues.

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[1] Certain software is identified in this paper in order to adequately specify the procedures used to produce the numerical results. Such identification does not imply that the software is necessarily the best available for the purpose.

APPENDIX - SENSITIVITY OF $e_m(\lambda)$

The sensitivity of the energy deposited in the varistor, $e_m(\infty, \lambda)$, to changes in the voltage rating of the MOV is given by

$$\frac{de_m(\infty, \lambda)}{d\lambda}.$$

This quantity can be determined by numerically integrating the model (4–7). However, this sensitivity can also be analyzed in closed form by considering the inductance-free, ($L = 0$), version of the model (Eq. 2 or 3). In this case, an algebraic expression for the sensitivity can be derived. It is shown to be accurate to within 15% over a significant range of values of λ.

The sensitivity of the energy dissipated in the MOV to changes in λ is most easily expressed in terms of the initial current through the varistor and the sensitivity of that current to changes in λ. In the inductance-free case, the initial conditions must be reformulated so that $i_m(0)$ is non-zero. When the initial data is the capacitor charge, $q(0)$, as was the case with the inductive model, it is possible to find $i_m(0)$ by finding the root of the non-linear expression given by:

$$\begin{aligned} F(i_m, \lambda) &= (R_m(1 + \frac{R_s}{R_p}) + R_s)i_m \\ &+ (1 + \frac{R_s}{R_p})\lambda i_m^{1/p} + \frac{q(0)}{C} \qquad (8) \\ &= 0 \qquad (9) \end{aligned}$$

which is a direct translation of (3) in the case that $L = 0$.

This equation can be solved for $i_m(0)$ using a few iterations of Newton's (gradient) method. Furthermore, the sensitivity of i_m to changes in λ is given by:

$$\begin{aligned} \frac{di_m}{d\lambda} &= -\frac{\partial F}{\partial \lambda} \Big/ \frac{\partial F}{\partial i_m} \qquad (10) \\ &= -i_m^{\frac{1}{p}} \left(R_m + \frac{R_s R_p}{R_s + R_p} + \frac{\lambda}{p} i_m^{1/p-1} \right)^{-1}. \qquad (11) \end{aligned}$$

To find the energy deposited in the MOV, first consider the evolution of the varistor current, i_m. This time evolution is given by differentiating equation (3) and applying (1) and (6):

$$R_s \frac{di}{dt} + \frac{dv_m}{dt} = \frac{i}{C} \qquad \text{or} \qquad (12)$$

$$(R_s \frac{di}{di_m} + \frac{dv_m}{di_m}) \frac{di_m}{dt} = \frac{i}{C} \qquad (13)$$

This equation is separable, that is it has the form

$$dt = G(i_m) di_m.$$

Evaluating $G(i_m)$ and reducing one has

$$\begin{aligned} G(i_m) &= \frac{C}{i}(R_s \frac{di}{di_m} + \frac{dv_m}{di_m}) \\ &= C \frac{(R_s R_p + R_s R_m + R_p R_m) i_m + (R_s + R_p) i_m^{1/p} \lambda / p}{(R_p + R_m) i_m + \lambda i_m^{1/p}}. \end{aligned}$$

As a result of separability, the energy may be written as a time-independent integral in which λ appears as a parameter:

$$\begin{aligned} e_m(\infty, \lambda) &= \int_0^\infty v_m i_m \, dt \qquad (14) \\ &= \int_{i_m(0)}^0 v_m i_m G(i_m) di_m. \qquad (15) \end{aligned}$$

$$= C\Pi \int_{i_m(0)}^0 \left(\Sigma i_m + \frac{\lambda}{pR_m} \left[\frac{1}{R_s} + \frac{1}{R_p} \right] i_m^{1/p} \right) \times \frac{\lambda i^{1/p} + R_m i_m}{\lambda i^{1/p} + (R_m + R_p) i_m} di_m, \qquad (16)$$

where

$$\Pi = R_s R_p R_m \quad \text{and}$$

$$\Sigma = \frac{1}{R_s} + \frac{1}{R_p} + \frac{1}{R_m}.$$

Expansion in λ about the nominal voltage threshold for the varistor, that is in powers of $\Delta\lambda$ where $\lambda = \lambda_{nom} + \Delta\lambda$, gives the leading term for the sensitivity of e_m to changes in λ:

$$\frac{de_m(\infty, \lambda)}{d\lambda} = C R_s R_p R_m \left(\frac{1}{R_s} + \frac{1}{R_p} + \frac{1}{R_m} \right) i_m \frac{di_m}{d\lambda} \qquad (17)$$

The sensitivity (17) may be evaluated algebraically once i_m is known from solving (8–9). A comparison with the inductive model is displayed in Figure 8. The curve shows numerically determined values of $e_m(\lambda)$ for the inductive model in 'let-it-rip' mode. The straight line has a slope determined by evaluating expression (17). The same expression may be used without recomputing the initial current in the case that the voltage, and hence the current, is adjusted to a fixed value.

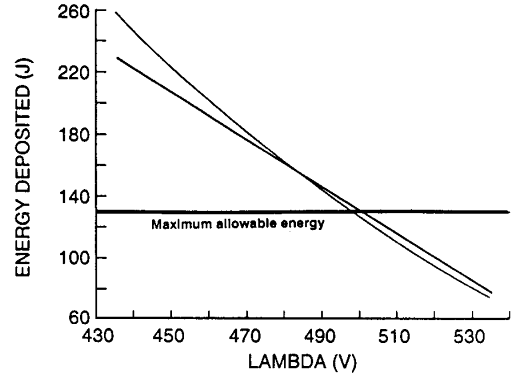

Figure 8. The energy dissipated in the MOV is displayed as a function of varistor rating, λ = 435 to 535 V. The straight line has a slope determined by Equation (17).

In either case, the sensitivity of i_m to changes in λ is small because $i_m^{1/p}$ in expression (11) depends so weakly on i_m. This may explain why, even though it is derived from the non-inductive model, this estimate of the sensitivity of the varistor energy deposition is so accurate.