TRANSIENT SUPPRESSOR DESIGN WITH VARISTOR COMPOSITE MATERIALS

INTRODUCTION

Transient suppression for electronic apparatus has always been a concern for design engineers. With modern electronic apparatus becoming more sensitive to malfunction or destruction by such transients, the need for transient suppression has become acute. One of the devices that has been used for this function is a varistor to clamp the transient over-voltage. This article deals not with how to select a discreet varistor for a particular application, but how to custom design a varistor using recently available varistor potting compounds, coatings, paints and other forms of powder-filled-vehicle composite materials.

DESCRIPTION OF THE MATERIAL'S PROPERTIES

Powder-filled-vehicle conductive composites possessing varistor-type/conductivity have been around for years. It has only been recently that they have received increased attention due to the increased demands for transient protection. Unlike high conductivity composites used for EMI shielding, i.e., sprays, caulks, adhesives, gaskets, where one tries to have maximum conductivity, varistor composites have a controlled voltage-dependent conductivity. In addition to the dc current increasing rapidly with voltage, the bulk dielectric constant also increases rapidly with voltage from a value of 10 to 20 for low to medium voltage, to over 1000 at voltages above the conduction knee. The mechanism for the capacitance increase is a statistical one attributed to progressively "shorting out" more junctions in the powder matrix, along with their capacitance, as the voltage is raised. The basic mechanism responsible for both of these resistive and capacitive effects is extremely fast particle junction conduction in the sub-nanosecond range. If one compares the voltage-dependent resistive and capacitive currents, one finds the capacitive currents dominant for pulses on the order of 0.4 microsecond and shorter, and resistance currents dominant for times longer than this regardless of the voltage. This fast fundamental junction conduction mechanism is responsible for both the non-linear resistance and the non-linear capacitance effects.

MATERIAL CHARACTERIZATION

The dc current voltage relationship of a finished device is directly attributable to the relationship between the material's intrinsic bulk properties:

$$J = B \cdot E^N \qquad \text{Equation 1}$$

where J= current density in amps/unit area; E= electric field gradient in volts/unit length; B and N are constants of the material and typically $N \sim 5$.

A plot of this relationship is shown in Figure 1, which resembles that of two back-to-back Zener diodes or Metal Oxide Varistors (MOV's), except that the curves in Figure 1 have rounder, softer knees. If one tries to relate the extrinsic properties of discreet devices, such as Zeners and MOV's, with intrinsic properties of the material, one has the relationships shown in Table 1.

Parameter	Extrinsic	Intrinsic	
	Units, Discreet Device	Units, Varistor Material	Typical Varistor Material Values or Operating Range
Voltage	Volts, V	Volts/inch, E	1000-100K V/in.
Current	Amperes, I	Amps/in.^{2}, J	10^{-4}–10^3 amps/in.^{2}
Maximum Power	Watts, P	Watts/in.^{3}, p	10 for dc, 10^6 for pulse
Maximum Fast Pulse Energy Dissipated	Joules, Q	Joules/in.^{3}, q	10 J/in.^{3}-no effect; 25 -some effect; 100 -failure for bulk material; (all higher for film material)
Capacitance	Picofarad, C	Dielectric Constant, K	K = 10 to 10,000
Resistive to Capacitive Transition Time	(no comparable parameter)	Microseconds	about 0.4 μs.
Response Time (time between V applied & current)	50 ns (diodes & MOV's) 100 ns-10μs (gas tubes)	Nanoseconds	Subnanosecond

Table 1. Comparison Of Discreet Device Extrinsic Properties With Varistor Material Intrinsic Properties.

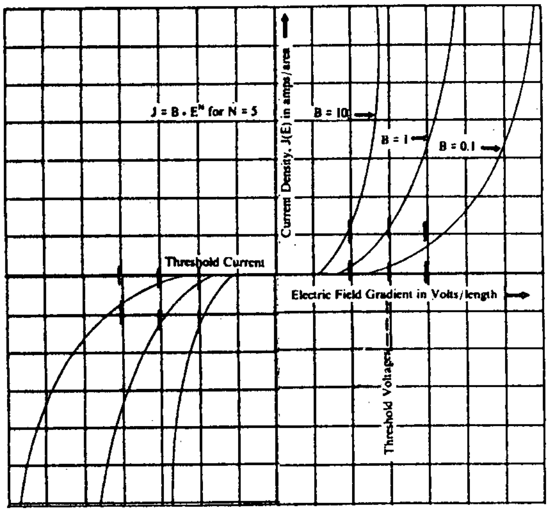

Figure 1. Plot of equation J=B·E^N for various values of B, all in arbitrary units & N = 5.

Figure 2 shows the current-voltage data of Figure 1 on a log-log plot along with a simultaneous plot of varistor material bulk dielectric constant, K (relative), versus voltage. This K was determined by measuring the peak-to-peak capacitive component of charge through the material from a high voltage pulse. To a close approximation, the slope of the dc current density — electric field gradient curve is N~5; the slope of the dielectric constant — electric field curve approaches N-1 ~ 4. This latter relationship holds in the region of high voltages above the knee, but deviates in the low voltage region where it asymptotically approaches a constant value on the order of 10 to 20 as shown in Figure 3. Due to this combined non-linear dc conductivity and non-linear dielectric constant, some very desirable effects are produced:

1) The higher the voltage, the higher the clamping action;
2) The faster the pulse, and the higher its voltage, the greater the clamping action due to the steep increase of capacitance with voltage;
3) Due to the combined effects of the non-linear conductivity and capacitance, energy from very fast high voltage pulses is first stored capacitively, and then dissipated much more slowly resistively.

RESPONSE TO EXPONENTIAL PULSE SOURCES

In order to completely engineer a given material to perform a given clamping function to a given source pulse, one must know, in addition to the pulse parameters, the interrelation between the material's physical dimensions and its extrinsic electrical properties. If the material were linear with a constant resistivity and dielectric constant, it would be a trivial matter for a given geometry to write an expression for its response to an applied source pulse. The varistor non-linearity expression of Equation 1, plus its capacitive non-linearity, would normally rule out any hope of finding an analytical expression for the material's response. Fortunately the material's resistive non-linearity and its capacitive non-linearity combine in a way that allows for a derivation of an exact expression for the response.

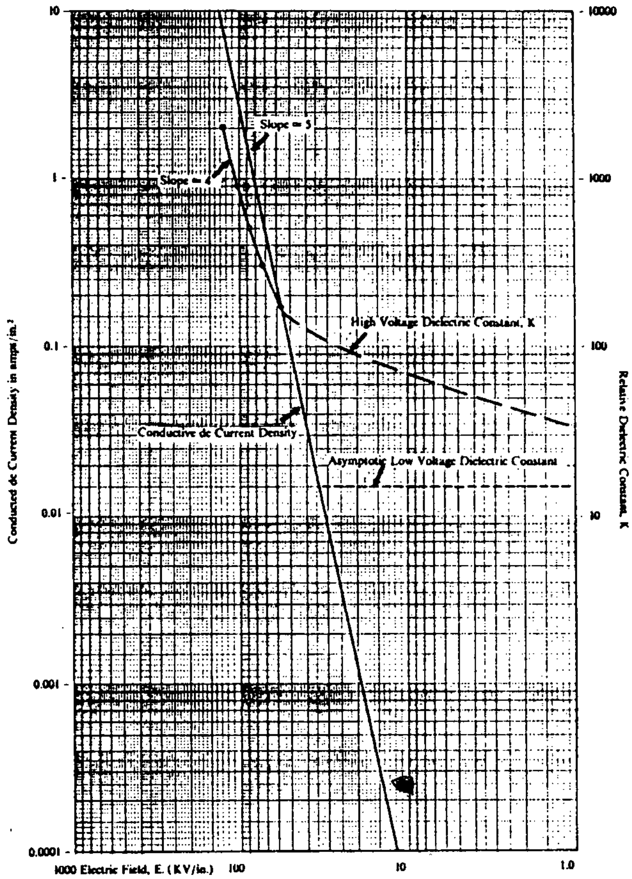

Figure 2. Conducted dc current energy & h.v. dielectric constant vs. electric field, E.

The non-linearity expression of Equation 1 may be a concise way of expressing the relationship, but it is cumbersome in terms of incorporating graphically-determined numerical data into the expression. A better way of expressing the data is given in Equation 2:

$$\frac{J}{J_0} = \left(\frac{E}{E_0}\right)^N \qquad \text{Equation 2}$$

where (E_0, J_0) is any point on the material's J-E graph. It was also noted above that the capacitance or dielectric constant in Figure 2 varied very closely as the N-1 power of E. Therefore it also can be written in the same form:

$$\frac{k}{k_0} = \frac{K\,.e_0}{K_0.e_0} = \frac{K}{K_0} = \left(\frac{E}{E_0}\right)^{N-1} \qquad \text{Equation 3}$$

where e_0 = the absolute permittivity of space = 0.225×10^{-12} F/in., k = Ke_0 = absolute material permittivity, K = relative material permittivity or dielectric constant, and (E_0, k_0) and (E_0, K_0) are any points on the respective curves provided one uses the same E_0 for both Equations 2 and 3.

In the particular case where total transient current equals:

$$I_t(t) = I_o \exp(-t/T_s) \qquad \text{Equation 4}$$

the solution for resistive or power-dissipative current is:

$$J(t)/J_o = (E(t)/E_o)^N = \frac{I_o}{A\,J_o\,(1-r)}\left[\exp(-t/T_s) - \exp(-t/T_M)\right]$$

Equation 5

where T_M = material characteristic time, T_s = pulse source characteristic decay time, and $r=T_M/T_s$ = dimensioness constant.

A plot of J(t) together with the applied pulse current, I_t, is shown on Figure 4.

Another result derivable from the time integral of Equation 5 from 0 to t_m is the charge, Q(t):

$$Q(t)=A \cdot J(t) \cdot dt = I_o \cdot T_s \cdot \left[\left(\frac{r \cdot \exp(-t/T_M) - \exp(-t/T_s)}{1-r}\right)+1\right]$$

Equation 6

The value of $Q(t_m)$ is:

$$Q(t_m) = Q_1 = I_o T_s \left[\frac{rr^{r/(1-r)} - rr^{1/(1-r)}}{1-r}+1\right]$$ (by substituting r for T_M/T_s) where T_M = time of maximum varistor voltage.

Equation 7

Of course the total Q from 0 to infinity is the total charge stored on the source capacitor:

$$Q_T \equiv Q(t=\infty) \equiv Q_t = I_o \cdot T_s = (V/R) \cdot (R \cdot C) = V \cdot C$$

Equation 8

where V,R & C are the internal values of the pulser.

This is exactly what one would expect, giving credibility to the derivations.

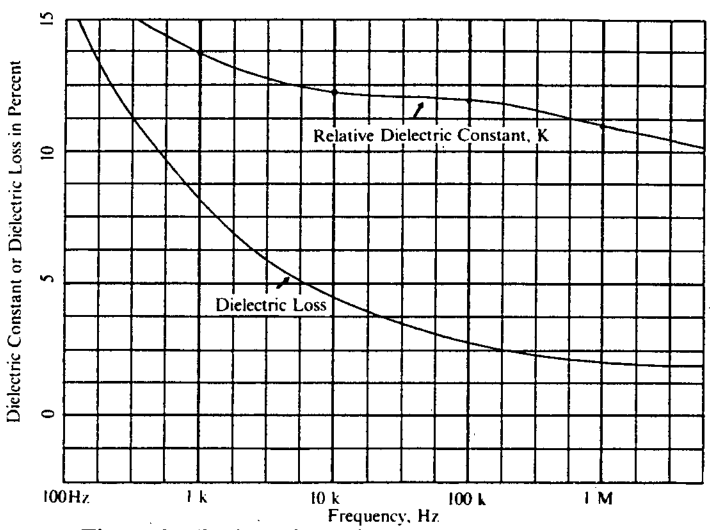

Figure 3. Typical dielectric constant & loss of varistor composite materials vs. frequency for low voltages, where electrical properties are essentially linear with voltage.

ENERGY CONSIDERATIONS

The problem of determining instantaneous power or power density in the material is a straightforward one of simply taking the EJ product. Determining the total joule energy dissipated in the material is considerably more difficult because it involves integrating the right hand side of Equation 5 to the power $1 + 1/N$, the exponent of the EJ product. Since the voltage or field remains fairly flat for wide variations in current, one can treat it as a constant and take it outside the integral. The exact solution then becomes the approximation:

$$w = \int p(t) \cdot dt = \int E(t) \cdot J(t) \cdot dt \cong E_m \cdot \int J(t)\,dt = E_m \cdot q_T = E_m \cdot \frac{Q_T}{A}$$

Equation 9

where q_T is the total charge density through the material in coul/in.².

The total *charge* through the material from the transient current source, Q_t is simply the slab area, A times q_t. One can see from Equation 9 that the ratio of the power dissipated in the varistor material in two situations, i.e., with and without the non-linear capacitance term, is simply $f \equiv r^{r/(1-r)}$. The capacitance reduces the peak dissipative current by f and the peak field by the nth root of this or $f^{1/N}$

SIZING A SLAB OF VARISTOR MATERIAL FOR A GIVEN PULSE

From the required clamping voltage one can determine the slab thickness, h, by using:

$$h \cdot E_m = V_c$$

Equation 10

There are infinite numbers of combinations of h and A that will give a given V_c. Some of these may give results that would push the energy density of the material beyond its capacity and result in a burnout. An important piece of information to know is: what are the minimum dimensions of the slab that will safely perform the required clamping function on the given pulse without burnout? The derivation shows that the slab area is determined by the pulse parameters and the thickness is determined by the clamping voltage requirement as follows. If one is *given* the material's energy density absorbing ability, w, then one can determine the slab area, A, in terms of w and the pulse parameters by:

$$w = E_o \cdot T_s \left(\frac{I_o}{A}\right)^{(1+1/N)} \left(\frac{f(r)}{J_o}\right)^{1/N} \qquad \text{Equation 11}$$

Solving for the minimum area, A_m gives:

$$A_m = I_o \cdot \left(\frac{E_o \cdot T_s}{w}\right)^{N/(N+1)} \cdot \left(\frac{f}{J_o}\right)^{1/(N+1)} \qquad \text{Equation 12}$$

One can use this equation and plug in the pulse source parameters and material parameters to obtain A_m. From A_m one can obtain E_m and J_m. From E_m one can use Equation 10 to know the h to build an effective varistor. If

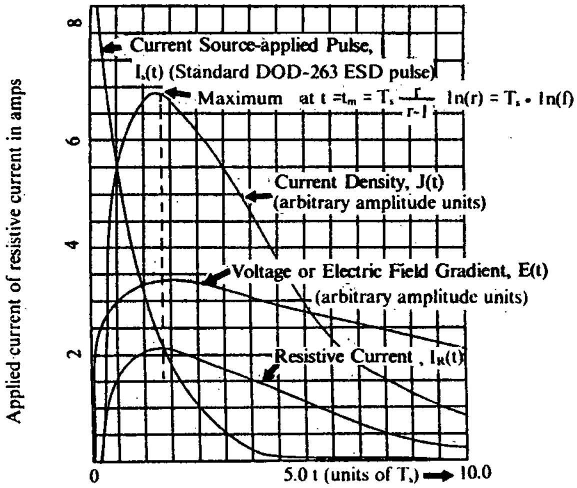

Figure 4. Plot of applied pulse current, resistive current, and current density and Varistor electric field vs time

one has room for a larger slab, then one can just choose the largest allowable value of A, and proceed with the rest of the above procedure. As one increases the area while still maintaining a given electrical spec of the slab, the thickness will only vary as the 1/N power of the area. As a general rule, one desires a larger slab rather than a smaller one, since it makes for easier fabrication and greater energy margins.

EXAMPLES OF APPLICATIONS

Rectifiers - Incorporation of varistor silicone rubber or potting compound inside a rectifier case to protect against reverse voltage transients.

Detonators - Use of varistor gasket rubber or potting compound in a detonator device to protect against electrostatic discharge (ESD) accidental detonation.

Burglar Alarm Circuit Boards - Protecting incoming lines to PC boards from lightning-induced transients via a varistor coating along with the terminal strip replaces dozens of discreet varistors.

Gas Tubes - Used to augment slower gas tubes for telephone and other applications.

DIP Protector - Flat geometry male-female transient protector adaptor between DIP and mother board.

Power Line Protectors - Between 110V line and sensitive electronic equipment.

CORONA SUPPRESSION

Another application area for varistor paints is the suppression of corona in air. The operation is due to the fact that the current through the paint depends directly on the *field* through it rather than the *voltage*. If the knee of the J-E curve is less than the air breakdown field, then no corona occurs in the air next to the paint. Typical places where corona may occur would be: high voltage bushings, power utilities equipment, high voltage cables for lasers and radar. The most likely spot is at the triple interface between a conductor at high voltage, a dielectric material, and air. To illustrate this application, the high voltage coaxial cable shown in Figure 4 will be assumed. The inside conductor is at high voltage ac or impulse. A good high voltage cable has resistive intermediate layers interfacing the dielectric to the inner conductor and to the cable shielding, and should have no internal corona. However, one must bare back the shielding before making contact with the central conductor or else it would short the conductor to ground. At the point where the shield departs from the insulation or where the shield ends abruptly is the spot prone to corona. This is because one has a discontinuous change in the dielectric's surface potential. To remedy this, one puts a short extension of varistor paint on the surface of the cable's dielectric. This grades the longitudinal field along the cable which indirectly grades the radial field component in the air. Figure 4 shows a plot of the voltage profile along the paint. Normally it would be a step function and very prone to corona, but with the paint it is virtually a linear drop-off.

SUMMARY

The above discussion on varistor powder-filled-vehicle composites is intended to acquaint the design engineer with a new, more versatile type of technology for transient and corona suppression than those presently available. Both the varistor conductive current and dielectric constant are typically shown to increase rapidly with voltage by about the 5th and 4th powers of voltage respectively. While the low-voltage dielectric constant is on the order of 10 to 20, the high voltage dielectric constant exceeds several thousand in the region of the current knee. This combined effect gives the material a characteristic transition time from non-linear conductor to non-linear capacitor of about 0.4 microsecond. The response time of this non-linear capacitance extends down into the subnanosecond range which is the particle junction-conductivity response time. Due to this effect, energy from very fast pulses (like ESD & EMP) is first stored capacitively and then dissipated resistively over times on the order of microseconds. This capacitive effect reduces the peak joules dissipated in the material for a given application and reduces the peak watts dissipated even more drastically. The qualitative time behavior of the material's response to a given transient depends explicitly on r, the ratio of the material's characteristic transition time to the pulse decay time.

The main purpose of this article is to make the design engineer aware of the tremendous potential of this type of material. In addition to making the engineer aware of these technologies, the article also provides him with the analytical design tools for actual cases.

This article was written for ITEM 85 *by Paul Malinaric, Electrostatic Consulting Associates, Groton, MA. For more detailed information, or to obtain additional derivations, contact the author.*